MRC
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THE PREDICTION OF SAFE EXPOSURE TIMES FOR MEN WORKING IN THERMALLY SEVERE ENVIRONMENTS

by

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SUMMARY

From a series of investigations begun in 1962 data have been collected on the times to imminent heat collapse of engine-room personnel, dressed in underpants, denim overalls, socks and shoes, and working at approximately 310 J/sec in extremely hot environments. A total of 87 men participated in the series and provided a total of 440 observations of exposure times in 21 different environments. The environments ranged in severity from 37.0/30.0°C dry-bulb/wet-bulb temperature, in which the majority of those exposed could work for 4 hr without attaining a state of imminent heat collapse, to 83.4/41.2°C db/wb in which the shortest time taken to reach imminent heat collapse was only 5 min.

Some environments had high relative humidity values and some had relatively dry atmospheres. In all conditions air and wall temperatures were approximately equivalent and air movement was maintained at either 0.76 or 1.02 m/sec.

The knowledge gained about individual differences in times to imminent heat collapse enabled nomograms and tables to be produced which permit durations of exposure to be determined within which a known proportion of exposees would be safe from the hazards of imminent heat collapse.

I INTRODUCTION

In 1962 a series of investigations was begun in which samples of Royal Naval engine-room personnel were exposed to high temperature environmental conditions until they attained a state of imminent heat collapse. This state was defined by the Warship Ventilation Panel of the RNPRC as one in which an exposee approaching heat collapse could still climb a 15 ft ladder and open a hatch as he would have to do in the emergency situation of a closed-down engine-room in H.M. Ships in the Tropics.

A work rate of approximately 325 J/sec was chosen as representing the level of energy expenditure which would be required in performing engine-room tasks under closed-down conditions. Conditions from those in which an exposee could remain without harm for at least four hours to those in which heat collapse would occur in the majority of exposees within five to ten minutes were chosen for inclusion in the investigations.

Because men differ widely in their tolerance of exposure to high temperature conditions it was decided that large numbers of exposees be examined in the investigations. From this individual variation a way was sought to establish safe-exposure times which would permit at least 95% of exposees to endure thermally severe conditions without suffering heat collapse during their exposure.

Eight men were exposed to six environments within a range from 37.0/30.0°C to 63.0/47.0°C dry-bulb/wet-bulb temperature with an air movement of 0.76 m/sec. Their responses to these exposures were reported to the RNPRC in Bell, Hellon, Hiorns, Nicol and Provins (1963). The responses of a further thirty-one men exposed to five environments within the range 37.5/33.9°C to 53.0/48.3°C dry-bulb/wet-bulb temperature with an air movement of 1.02 m/sec were described in Bell, Walters and Watts (1967). A further series of experiments has now been completed in which two groups each of 24 men were exposed to environments within the range 37.8/31.9°C to 83.4/41.2°C dry-bulb/wet-bulb temperature with an air movement of 1.02 m/sec.

The present report brings together a total of 440 observations from a total of 87 subjects exposed to 21 environments within the range 37.0/30.0°C to 83.4/41.2°C dry-bulb/wet-bulb temperature with air movements of 0.76 or 1.02 m/sec.

II METHOD

Subjects: Eighty-seven Naval personnel volunteered their participation in the investigations. All had experienced closed-down engine-room conditions in the Tropics but at the beginning of the investigations were no longer acclimatised to heat. One subject had the rank of Chief Ordnance Artificer and the rest were either M.E.'s or L.M.E.'s. Other subject characteristics are shown in Table 1. Body surface area was calculated for each subject individually. It will be noted in Table 1 that not all data were available for all participating subjects.

Table 1: Description of physical characteristics of volunteer subjects participating in the investigations

	Mean	Range	N
Age last birthday	22.2 years	18 - 29 years	87
Height in bare feet	174.1 cm	160 - 188 cm	77
Initial nude weight	70.70 kg	54.85 - 96.00 kg	87
Surface area	1.84 m^2	1.56 - 2.19 m^2	77

Design: The subjects attended the Climatic Physiology Laboratory of the Institute of Aviation Medicine for a period of five consecutive days from Monday to Friday. Each day they were exposed once to one of the climatic conditions which were arranged in a random order. These random orders in each investigation were reversed for half of the experimental subjects. Of the 48 subjects in the most recent of the investigations, there were 4 (8.3%) who were exposed to high temperature environments in two consecutive weeks. The group of 8 subjects who participated in the first series of experiments remained at the laboratory for two periods of five days separated by one weekend. Their data for inclusion in this report were taken from those exposures in which the subjects worked in a climatic condition for the first time on a particular day.

The environments included in these investigations ranged in dry-bulb temperatures from 37.0 to 83.4°C, in wet-bulb temperatures from 28.2 to 48.3°C and in relative humidity values from 9.3% to 83.6%. An attempt was made to choose climatic conditions which sampled adequately the area of thermal severity bounded by these values. Figure I illustrates the extent to which this attempt was successful.

Details of the physical parameters of the environments included in the investigation are shown in Table 2. Dry-bulb temperatures were controlled to within ±0.05°C and relative humidity was controlled to within ±1%. In Table 2 a value of the Normal Scale of Corrected Effective Temperature has been included for those climates which fell within the range of thermal severity served by the Effective Temperature nomograms. Some of the climatic conditions could be assessed also in terms of the P4SR index. By adding 1.8°F for clothing and 5.3°F for work-rate to the wet-bulb temperatures in °F of the climates, it was possible to extract from the P4SR nomograms values of 1.5, 3.1, 2.6 and 3.8 for the exposures to environments of 37.0/30.0, 37.8/31.9, 46.0/29.5 and 54.3/28.2°C dry-bulb/wet-bulb temperature respectively. All other conditions were outside the range of the P4SR nomogram.

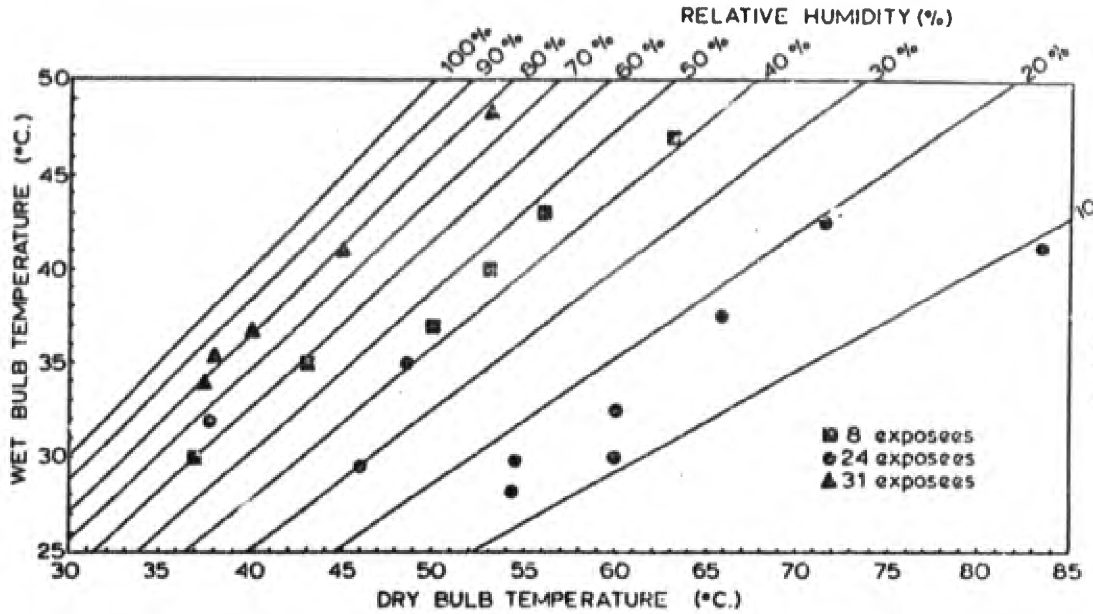


FIGURE I Environmental conditions to which 8 subjects (■), 24 subjects (●) or 31 subjects (▲) were exposed.

Table 2: Environmental conditions to which subjects working continuously at about 310 J/sec were exposed and in which dry-bulb and globe temperatures were equivalent

Climate	Dry-bulb °C	Wet-bulb °C	Relative humidity %	Air speed m/sec	Normal scale CET °C	Number of exposes
1	37.0	30.0	60	0.76	31.9	8
2	37.8	31.9	66	1.02	32.5	24
3	46.0	29.5	30	1.02	32.9	24
4	54.3	28.2	14	1.02	33.6	24
5	37.5	33.9	78	1.02	34.0	31
6	54.5	29.8	17	1.02	34.3	24
7	38.0	35.3	84	1.02	35.2	31
8	60.0	30.0	11	1.02	35.1	24
9	43.0	35.0	59	0.76	35.9	8
10	40.0	36.7	81	1.02	36.7	31
11	48.6	35.0	41	1.02	36.8	24
12	60.0	32.5	16	1.02	36.4	24
13	50.0	37.0	40	0.76	38.4	8
14	45.0	41.0	79	1.02	42.1	31
15	53.0	40.0	46	0.76	41.4	8
16	65.8	37.5	18	1.02	*	24
17	56.0	43.0	47	0.76	*	8
18	71.5	42.5	20	1.02	*	24
19	53.0	48.3	77	1.02	*	31
20	63.0	47.0	42	0.76	*	8
21	83.4	41.2	9	1.02	*	21

* Beyond the range of Corrected Effective Temperature Normal Scale

During exposures subjects wore underpants, denim boiler suits, socks and shoes. Throughout exposures, engine-room noise at approximately 90 decibels relative to the usual arbitrary zero of 0.0002 dynes/cm^2 was relayed over loudspeakers in the climatic laboratory. Lemon flavoured glucose drinks maintained at a temperature of 38°C were available on request to subjects during their exposures.

From entry into the hot chamber subjects followed a work routine requiring them to step on and off a stool 22.9 cm high in time with an indicator lamp which flashed at a rate of 12 times per minute. The energy cost of this activity was assessed on 11 subjects who performed the work routine in the recovery room. Their data is shown in Table 3 from which it may be seen that an average level of energy expenditure of approximately 310 J/sec was required in the performance of the work routine.

Table 3: Energy expenditure[1] of 11 clothed subjects performing a work routine of stepping on and off a stool 22.9 cm high at a rate of 12 times per min.

Subject	Age yr	Clothed weight kg	[2] Surface area m^2	[3] Energy J/sec	Expenditure J/kg/sec	J/m^2/sec
A	20	67.65	1.78	270	4.00	152
B	20	70.01	1.87	310	4.45	166
C	20	74.80	1.96	280	3.77	148
D	26	63.48	1.72	335	5.31	196
E	23	68.90	1.69	295	4.82	174
F	21	71.36	1.85	360	5.02	193
G	28	62.00	1.76	285	4.61	163
H	23	64.26	1.73	275	4.30	159
I	20	76.60	1.98	330	4.28	165
J	23	75.10	1.94	320	4.25	165
K	19	81.35	2.01	370	4.56	185
	22	70.50	1.84	312	4.49	170

[1] These studies were conducted, and the data analysed, by Mr S. Prestidge of the MRC Environmental Physiology Unit.

[2] Body surface areas calculated from DuBois nude height/nude weight formula.

[3] Energy expenditure calculated from tables of differing respiratory quotients (RQ's).

Routine and physiological measurements: Subjects remained at the laboratory throughout each day on which experimental exposures occurred. At approximately 30 - 45 min before his entry into the hot chamber each subject, after defaecating or urinating, undressed and was weighed nude. After putting on his hot-exposure clothes the subject then sat at rest in an ante-chamber until it was time for entry into the hot environment. During this pre-exposure period body temperature was assessed at intervals of about 5 min from an indwelling sub-lingual copper-constantan thermocouple for subjects in the investigations of 8 men and 31 men and from an indwelling ear thermister (held in place and insulated from the ambient room conditions by cotton wool and a rugby scrum cap) in the investigations of 24 men. Pulse rate by palpation at the wrist over 30 sec was recorded with a similar frequency by observers who were responsible for the pre- and post-exposure monitoring of the subjects.

Subjects entered the high temperature environments individually or in groups of up to 4 men depending upon the space available in the hot chamber. The chamber was so arranged that communication between subjects during exposures was discouraged. The subjects were not allowed to carry watches into the hot chamber and were prevented as far as possible from monitoring for themselves the duration of their exposure or how the duration of their own exposure compared to the duration of exposure of other subjects. Oral or inner ear temperatures were recorded, without the subjects' awareness, at frequent intervals throughout the exposure. Two experienced observers remained in the hot chamber with the exposees. The observers wore air-cooled protective garments. Information was transmitted via a two-way system of speakers to the hot-chamber observers about the subjects' temperatures. The observers themselves kept a record of the subjects' appearance, volume of lemon glucose drink consumed and pulse rates.

When the subject had attained a state of imminent heat collapse (see the next section) the ante-room observers were informed and they assisted the subject from the entrance of the hot chamber to the recovery room. Within minutes of the completion of the hot-exposure each subject undressed, was wiped down with a dry towel, and was weighed nude. He then put on a towelling dressing-gown and sat in a reclining chair whilst his recovery was monitored. Body temperatures and pulse rates were recorded until their values had returned to pre-exposure levels or had reached a steady state which had been maintained for at least 15 min.

These measurements provided information on:- (a) the duration of exposure to the high temperature environments from entry into the hot chamber to exit from the chamber; (b) the body temperature and pulse rate of the subject after entry into the hot chamber and the final body temperature and pulse rate recorded before the exposure was terminated; and (c) the weight losses of the subjects corrected for all intake and eliminations between weighings.

Imminent heat collapse criteria: The requirement in these investigations was that exposures should be terminated at a point, before heat collapse had occurred, which would enable exposees to leave the hot environment unaided. If the exposure had not been ended at this point, the exposees should have suffered heat collapse within the time it took them to reach the recovery room.

At the beginning of each series of experiments the aims of the investigation were described to each new group of exposees. It was explained that the study would have a practical value to serving members of H.M. Navy only if exposees pushed themselves to the limits of their endurance in the hot environments. Reassurance was given that the highly qualified and experienced observers would ensure that no harm came to exposees. These observers had a constant source of information about the condition of the exposee and they would advise when an exposure should be ended. As part of their assessment of the exposee's condition they would ask him how he felt and whether he could continue the exposure.

It was pointed out to the subjects that men varied considerably in their tolerance of heat and that sometimes an exposee would feel able to continue his exposure but would be sent out of the hot chamber by the expert observers and sometimes an exposee would feel unable to continue his exposure but would be encouraged by the observers to try for a few more minutes. It was emphasized that the subjects' participation in the investigation was voluntary and they retained the right to withdraw at any time. No subject did in fact withdraw from the experiments throughout the period of the study.

The hot-room observers took as guidelines to their common decision to terminate an exposure: (a) a high and rapidly rising body temperature (about 39°C or above depending upon the particular exposee) together with an irregular pulse rate or one of 100 beats per half-minute or more; (b) the general appearance of the exposee with particular attention being paid to his inability to perform the controlled stool-stepping routine but with some weight also being given to complaints about general tiredness, pains and feelings of nausea, and actual vomiting; and (c) the exposee's own persistently, and sometimes antagonistically, expressed opinion that he could not go on any further. Both observers were fully experienced in this type of investigation and one was always a medically qualified member of the Royal Navy with considerable experience of heat studies.

The physiological state of the exposees, as indicated by their body temperature, pulse rate and weight loss data, at the end of exposures is described in the results section below. From time to time during the investigations a few exposees had collapsed whilst they were leaving the hot-chamber. In these cases the exposee was assisted into an ante-room where he recovered rapidly.

On a few occasions during the first series of experiments on 8 men, exposures of up to 4 hours were terminated before imminent heat collapse had occurred because of extreme fatigue of the exposee's leg muscles. In all subsequent experiments exposures were terminated after 120 minutes if imminent heat collapse had not been reached before this time. The findings contained in this report describe, therefore, the safe exposure of engine-room personnel to thermally severe environments which can be tolerated for a period of up to two hours duration.

Analysis of the data: It was required to produce a general expression of a relationship between exposure durations and levels of climatic severity within the range studied which would enable 95% of exposees to avoid reaching a state of imminent heat collapse. The derivation of these 95% safe exposure times is described in the results section below.

III RESULTS

Imminent heat collapse times: The durations of exposure of the subjects in the twenty-one environments are shown in Table 4. It should be noted that data were missing from three exposees in the 83.4/41.2°C db/wb climate. In the case of two of these exposees equipment failure resulted in a marked drop in environmental temperature some way through the exposures. A third subject was not permitted to take part in the exposure to this particularly severe climate because he had a heavy head-cold on the day in question.

Table 4: Individual times to imminent heat collapse. *

Climate db/wb °C	N	Imminent heat collapse times in minutes**											
37.0/30.0	8	240+	240+	240+	240+	208	200	146	118				
37.8/31.9	24	120+	120+	120+	120+	120+	120+	120+	120+	120+	120+	120+	120+
		120+	120+	120+	120+	120+	120+	96	90	84	81	80	51
46.0/29.5	24	120+	120+	120+	120+	120+	120+	120+	120+	120+	120+	120+	117
		110	110	108	101	100	94	94	89	86	84	83	78
54.3/28.2	24	120+	120+	120+	120+	120+	92	89	83	83	80	78	65
		63	62	61	60	58	58	56	53	50	49	41	41
37.5/33.9	31	132	122	121	115	109	108	106	101	100	95	91	89
		85	85	83	83	83	81	81	80	78	76	74	73
		71	66	65	63	61	61	57					
54.5/29.8	24	106	102	77	75	74	73	73	70	70	69	65	64
		63	61	61	61	59	57	56	55	51	45	44	42
38.0/35.3	31	81	73	71	69	68	65	64	62	61	61	57	57
		56	55	54	54	53	52	51	51	49	47	47	46
		45	43	43	40	31	31	30					
60.0/30.0	24	68	63	63	57	55	55	51	48	47	46	46	46
		46	45	44	41	40	40	40	40	39	38	33	31
43.0/35.0	8	67	65	61	59	56	54	49	43				
40.0/36.7	31	68	55	54	53	51	51	51	49	48	48	48	47
		45	45	44	44	44	43	42	42	40	40	40	37
		37	37	36	35	35	30	27					
48.6/35.0	24	76	72	66	60	60	56	54	54	52	50	49	48
		48	45	43	42	42	39	39	39	39	37	37	36
60.0/32.5	24	58	58	57	51	51	49	48	46	44	44	42	42
		42	41	41	41	40	40	39	39	38	37	33	30
50.0/37.0	8	53	49	42	40	35	35	31	29				
45.0/41.0	31	35	35	33	33	33	32	31	30	29	29	29	27
		27	26	26	26	25	25	25	24	24	23	23	22
		22	22	22	21	19	19	19					
53.0/40.0	8	24	23	23	22	21	20	19	19				
65.8/37.5	24	36	35	35	34	31	30	30	29	29	28	27	27
		27	26	25	25	25	24	23	23	22	21	21	19
56.0/43.0	8	19	19	17	17	16	15	14	11				
71.5/42.5	24	24	24	23	21	21	21	20	20	20	20	19	18
		18	18	18	17	17	17	17	16	14	14	10	9
53.0/48.3	31	15	15	15	14	14	14	14	13	13	13	13	13
		13	13	13	12	12	12	12	12	12	11	11	11
		10	10	10	9	9	9	9					
63.0/47.0	8	14	13	13	12	11	10	8	6				
83.4/41.2	21	24	21	20	19	18	18	16	16	16	16	16	15
		15	14	14	11	11	10	10	9	5			

* Within each climate the times are shown in descending order of magnitude not in subject-order.

** Values shown as 240+ or as 120+ indicate that the exposure was terminated before a state of imminent heat collapse had been reached.

In the Table it will be noted that on 38 occasions (8.6%) the exposures were terminated before the subject had reached a state of imminent heat collapse. This gives rise to data which are said to be right-censored. For these an observation is made not of an actual time to imminent heat collapse but only that imminent heat collapse time would be greater than some value (i.e. 120 or 240 min in these experiments). The proportion of such occasions can be seen in the Table to decrease with increasing climatic severity. Within the range of climates studied, the longest exposure time which was ended when the exposee had reached a state of imminent heat collapse was 208 min and the shortest such duration was 5 min.

Initial (maximum likelihood) estimation of means and variances of the imminent heat collapse time data within each of the 21 environments revealed a marked heterogeneity of variances. Significant departure from homogeneity was also evident when the raw data were transformed into reciprocals. A log transformation of the data, however, reduced the inequality of the variances to an acceptable level (χ^2=29.3 at d.f. = 20; $p>0.05$) and produced non-skewed distributions in all but two of the climates without censored data. In the 71.5/42.5°C db/wb climate the slight negative skewness came from the 9 and 10 min values and from the single value of 5 min in the 83.4/41.2°C db/wb climate.

At low levels of thermal severity the exposee's thermal equilibrium may be maintained for a considerable period of time. At very high levels of thermal stress the minimum time in which a body can be heated up to an imminent collapse point may be close to zero. A plausible model, therefore, relating imminent heat collapse times to environmental severity is a rectangular hyperbola with horizontal asymptote zero. Such a model was employed in the description of an earlier series of investigations of the responses to exposure of 8 men. In using this model it must be acknowledged that exposees in the mildest climates would not be able to continue their exposure indefinitely if they were required to perform a stool-stepping task continuously. Muscular fatigue would place a limit on the duration of this activity and hence upon the duration of their exposure. Similarly, it must be acknowledged that before levels of thermal severity are reached in which imminent heat collapse occurs in almost zero time distress to exposees caused by burning or scalding of exposed skin surfaces would prevent entry into such environments.

With the range of climatic severity contained in the present investigations, however, from those in which exposees could remain for four hours without demonstrating imminent heat collapse to those in which short durations of exposure to imminent heat collapse were accompanied by unpleasant skin sensations, it was decided to use the hyperbolic model:

$$\text{imminent heat collapse time} = \frac{b}{c - a}$$

where a and b are parameters to be estimated and c represents a measure of climatic severity. In the present analysis c was taken to be w dry-bulb + (1 - w) wet-bulb temperature in °C where w is a weighting coefficient to be estimated.

The regression equation to be fitted to the data was thus:

$$y_i = \log\left(\frac{b}{c_i - a}\right) + e_i$$

where y is log time to imminent heat collapse and e_i is the error associated with the i th observation (of which there were 440 in all). The e_i were assumed to be independently normally distributed with mean zero and a constant variance to be estimated of σ^2. Assumptions of normality and constancy of variance motivate the log transformation which was employed. The assumption of independence ignores the fact that each man provided observations in several climates. This appeared permissible in the achievement of a relatively simple formulation of the problem and was checked later by examining individual subjects' departures from the fitted model. Using a theory similar to that described by Glasser (1965) for linear regression, the censored data were accommodated in the non-linear regression of the present analysis.

The estimated values and standard errors of the parameters a, b, w, and σ are shown in Table 5. They indicate that a climate description comprising

$$0.22661 \quad db + 0.77339 \ wb \quad ^{o}C$$

is a suitable measure of environmental severity for the present data.

Table 5: Estimated values for the parameters of the rectangular hyperbolic model of the relationship between times to imminent heat collapse and climate severity.

Parameter	a	b	w	σ
Estimate	30.546	302.26	0.22661	0.27662
Standard error	0.990	6.35	0.00726	0.00981

A plot of the curve fitted to the data and of the 21 estimated mean times to imminent heat collapse is shown in Figure II. These mean values were estimated separately for each climate by the maximum likelihood method with the assumption of a normal distribution of log times to imminent heat collapse within climates. In environments in which no censored data were produced these estimates are the usual sample means and variances.

The adequacy of the fitted model and the validity of the assumptions made were checked in several ways. Mean residuals were obtained by taking the differences between the 21 estimated mean imminent heat collapse times and the corresponding values obtained from the regression equation. These mean residuals were plotted against various possible additional factors that might have been suggested for inclusion in the model - for example a relative humidity factor. No visual evidence of such deficiencies in the model could be identified.

A further test was made of the adequacy of the model. From each of the 440 data points was subtracted a corresponding value derived from the regression equation. Each of these residuals was standardized by dividing it by the estimate of the residual standard error (σ in Table 5). A full normal Q-Q plot of these standardized residuals was made following Wilk and Granadesikan (1968). Although there was evidence of some curvature in the plot reflecting a small amount of negative skewness in the distribution of the residuals, there was no serious departure from expectation of a set of (almost) independent N(0, 1) observations. The presence of right-censored observations, which had been given their censored value for the plot (i.e. 120 or 240 min) made its interpretation more complicated as it was not possible to state that all such points had occurred in one section, for instance the top right hand corner, of the plot.

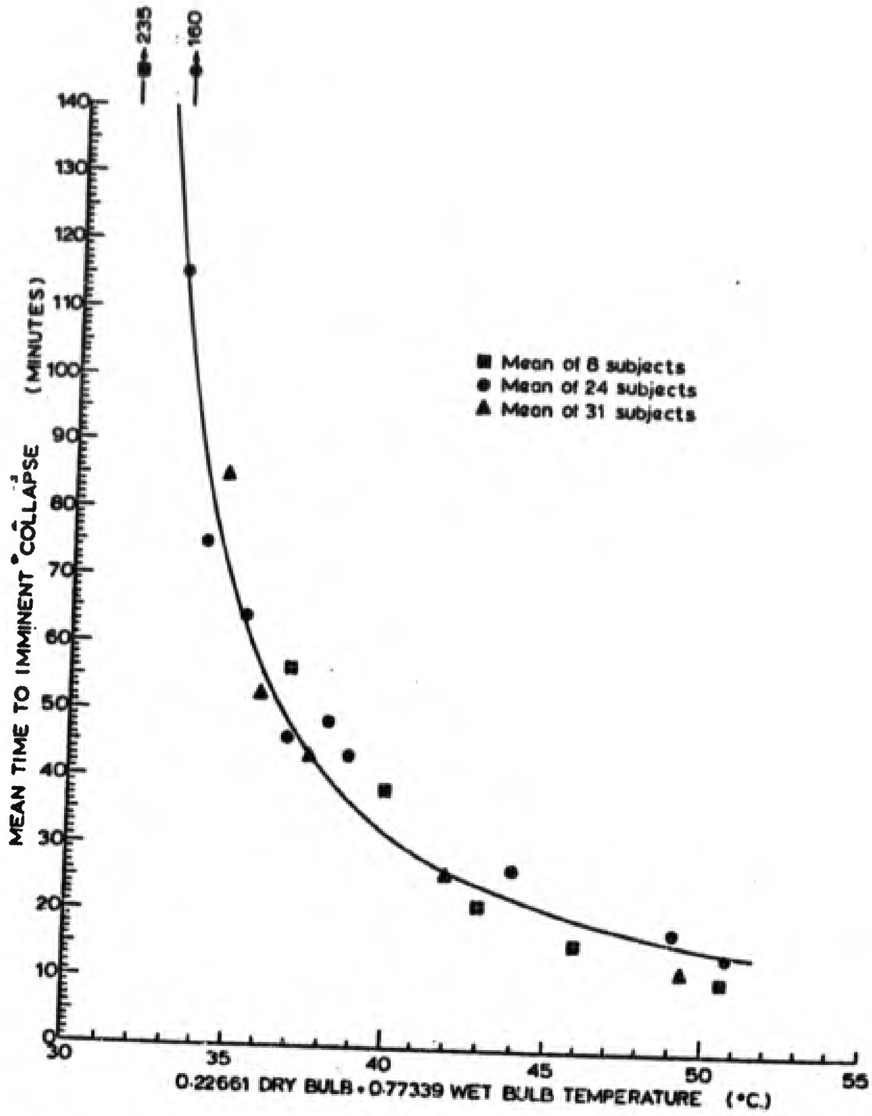


FIGURE II Predicted mean times to imminent heat collapse and observed mean times from 8 men (■), 24 men (●) and 31 men (▲).

Finally, the 440 residuals were grouped according to subjects. No clear patterns for particular subjects could be identified. It appeared therefore, that the assumption of independence of the 440 data points upon which the regression analysis was based had not been contradicted.

Predicted mean times to imminent heat collapse are shown in Table A of the Annex and in the form of a nomograph in Figure III.

Safe exposure times: The reason for deriving a general formula describing the dependence of imminent heat collapse times on climatic severity was to provide a means whereby a time limit could be ascertained, for any combination of dry-bulb and wet-bulb temperatures within the range studied, within which a given proportion of exposees would not suffer imminent heat collapse. These 'Safe Exposure Times' are taken from lower confidence limits for individual observations. Thus to obtain safe exposure times which will protect p% of exposees from collapse, it can be shown that the lower p% limit is

$$y - t_p s$$

In this expression y is the predicted log time to imminent heat collapse obtained from

$$\log \left(\frac{b}{c - a} \right)$$

in which c represents a climate of w dry-bulb + (1 - w) wet-bulb temperature in ^{o}C. The term t_p indicates the lower p% point of 't' with 440-4 degrees of freedom. The s term derives from

$$s^2 = \sigma^2 + \underline{x}^T H \underline{x}$$

where $\underline{x}$ is the vector (transpose of)

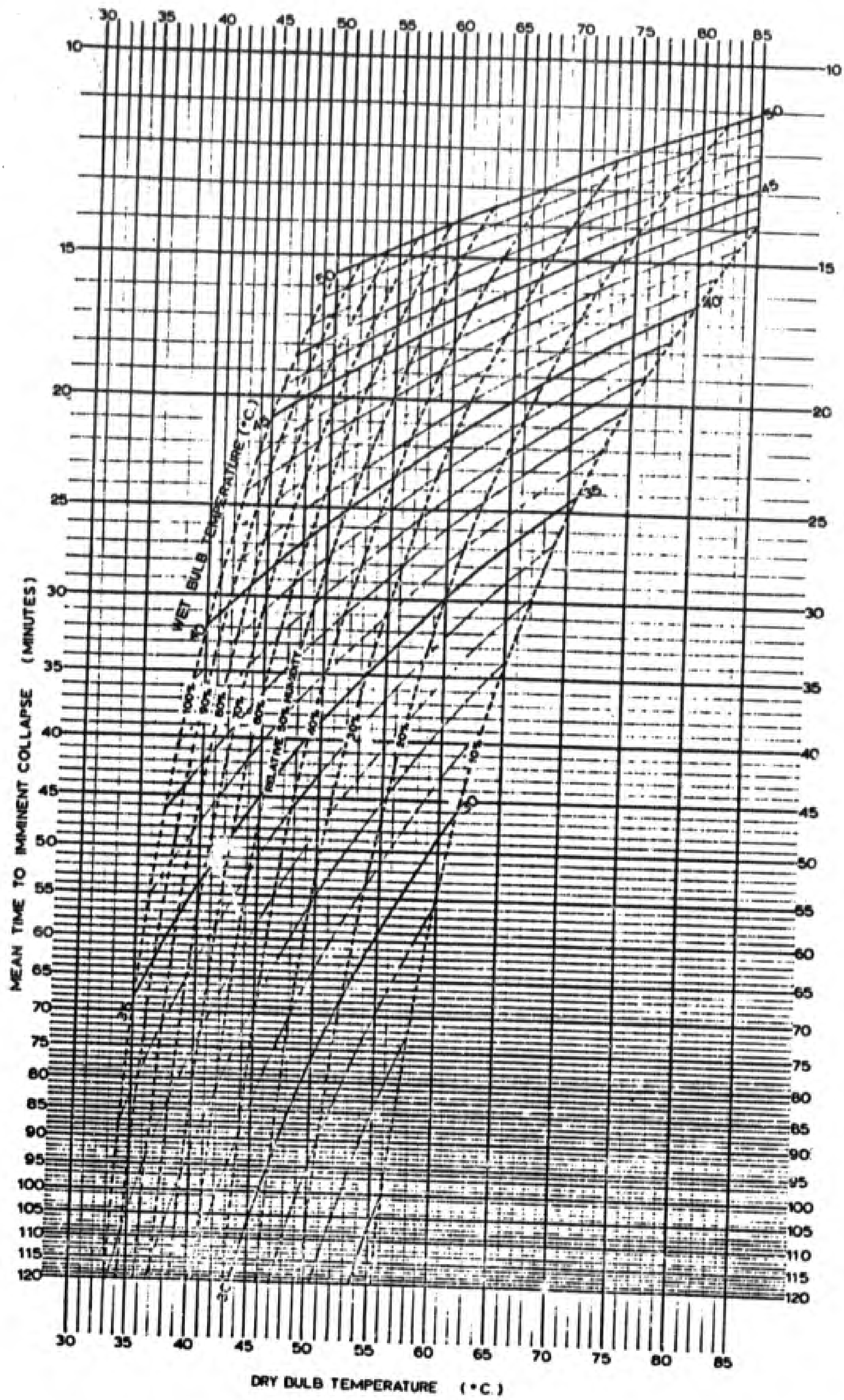
$$\left(1, \ - \frac{db - wb}{c - a}, \ \frac{1}{c-a}, \ 0 \right)$$

and H is the covariance matrix of the parameters a, b, w, and σ

It was found that because $\underline{x}^T H \underline{x}$ was small compared to σ^2, over the range of dry and wet bulb temperatures investigated, the value of s, and consequently of $t_p s$, was almost constant. Thus an expression can be written of the lower p% safe exposure time as

$$\text{lower safe exposure time} = \exp(y - t_p s) = K_p \exp(y)$$

where K_p is a factor depending only on p. As a check on this conclusion a large number of safe exposure times were computed and were found to confirm the expectations. Safe exposure times for the range of conditions and the work rate employed in the present investigations for 75%, 80%, 90%, 95% and 99% of exposee populations represented by the subjects studied here may be derived from the predicted mean imminent collapse times and the values shown in Table 6. These derived safe exposure times are shown in Tables B to F of the Annex.



NOT REPRODUCIBLE

FIGURE III Nomogram of mean times to imminent heat collapse in relation to dry-bulb temperature, wet-bulb temperature and relative humidity.

Table 6: Safe exposure times for various percentages of exposees expressed as a proportion of the predicted mean time to imminent heat collapse.

Percentage safe exposure (p%)	50	75	80	90	95	99
Proportion of mean time (K_p)	1.0000	0.8290	0.7911	0.6999	0.6327	0.5235

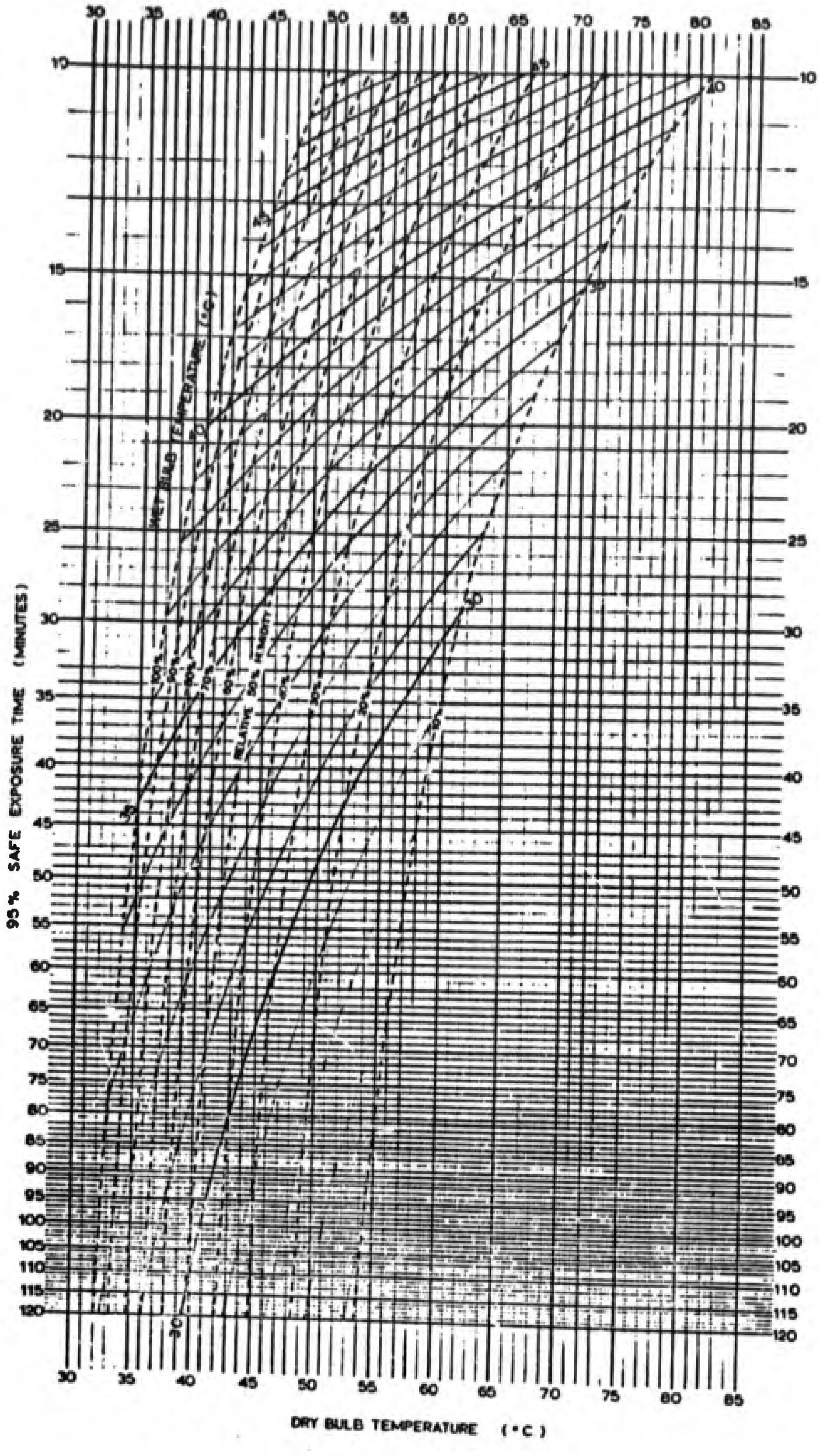
A nomogram of 95% safe exposure times in relation to dry-bulb and wet-bulb temperature and relative humidity is shown in Figure IV.

Physiological data

A summary of the weight loss, pulse rate and mouth or ear temperature data from the investigations is given below. It should be noted that these data were not recorded with specific purpose of describing the heat collapse syndrome. It was for this reason that automatic monitoring of physiological parameters was not employed in the present research.

Weight loss: The means and standard deviations of the nude weights of the subjects before exposure and the corrected weights after exposure to heat are shown in Table 7. A rate of weight loss based upon a division of the weight loss incurred during an exposure by the duration, in minutes, of exposure was calculated for each subject in each environment. The means and standard deviations of these values, which took no account of the time to onset of sweating from entry into the heat, are also shown in Table 7. In the Table those exposures which were terminated, at 120 min, before imminent heat collapse had occurred are shown separately. It will be noted that the experiments involving 8 subjects in which dry nude weight was not recorded are omitted from the Table.

There seems to be some indication in the Table that rate of weight loss appeared to increase with greater climatic severity (and hence shorter exposure time).



NOT REPRODUCIBLE

FIGURE IV Nomogram of 95% safe exposure times in relation to dry-bulb temperature, wet-bulb temperature and relative humidity.

Table 7: Weight loss of men working continuously at 268 kcal/hr during exposure to high temperature environments

Climate db/wb °C	Pre-exposure nude weight kg		Post-exposure corrected nude weight kg		Rate of weight loss g/min		Number of exposees
	Mean	s.d.	Mean	s.d.	Mean	s.d.	
37.8/31.9	69.50	8.36	67.91	8.23	13.26	2.56	18*
	74.46	11.63	73.46	12.36	12.97	3.91	6
	70.74	9.27	69.30	9.21	13.18	2.86	24
46.0/29.5	68.82	6.58	66.97	6.53	15.41	1.72	11*
	70.84	12.66	69.80	12.55	10.93	2.43	13
	69.92	10.17	68.50	10.13	12.98	2.28	24
54.3/28.2	66.55	7.16	64.11	7.00	20.32	2.79	5*
	70.44	10.71	69.46	10.60	14.86	3.76	19
	69.63	10.07	68.35	10.07	16.00	4.18	24
37.5/33.9	70.74	9.72	69.41	9.61	15.67	4.60	31
54.5/29.8	70.30	9.31	69.25	9.22	16.08	2.91	24
38.0/35.3	70.82	9.58	70.02	9.52	15.16	4.96	31
60.0/30.0	70.08	10.04	69.21	10.03	18.73	4.95	24
40.0/36.7	70.99	9.53	70.25	9.50	16.79	4.47	31
48.6/35.0	69.73	10.09	68.90	10.08	16.52	6.61	24
60.0/32.5	70.81	9.22	69.93	9.13	19.97	3.68	24
45.0/41.0	70.77	9.61	70.28	9.53	18.37	7.01	31
65.8/37.5	70.68	9.16	70.09	9.12	21.85	4.70	24
71.5/42.5	69.76	10.21	69.35	10.18	22.88	6.31	24
53.0/48.3	70.69	9.73	70.15	9.54	20.21	9.68	31
83.4/41.2	71.64	8.99	71.17	8.98	30.83	8.98	21

*These exposures terminated before imminent heat collapse

However, two qualifications are necessary in respect of the weight loss data. Firstly, sweat onset and sweat losses were not monitored within exposures and a variable time occurred between the termination of an exposure and the post-exposure nude weighing. Secondly, as can be seen clearly in Table 7, the variance values associated with each of the mean rates of weight loss are sufficiently large to reflect a considerable overlap between climates. For these reasons no further analyses of these data were undertaken.

Pulse rate: The means and standard deviations of the pulse rates over 60 sec are summarised in Table 8. All the data shown in the Table come from assessments of pulse rate during exposures. These assessments were made by the hot-chamber observers. When a pulse rate was too fast for the observer to complete a count of pulse beats over a period of 30 sec he noted his maximum possible count and recorded the pulse as being in excess of that value. Observers differed in their ability to monitor rapid pulse rates. This ability was also affected by individual differences between exposees in the relative ease or difficulty with which their pulse beat could be detected and monitored with the exposee in good condition. An increasing problem of maintaining contact with their pulse beat occurred when the exposees began to stagger and stumble as their imminent heat collapse approached. For these reasons, the data shown in Table 8 should not be equated with the kind of heart rate data which would have been produced if automatic methods of monitoring had been used to study the physiology of heat collapse.

There appeared to be no systematic tendency for the final pulse rate data to be related to climatic severity.

Table 8: Pulse rates of men working continuously at approximately 310 J/sec during exposure to high temperature environments

Climate	Initial pulse rate beats/min		Time after entry min	Final pulse rate beats/min		Time before collapse min	Increase in pulse rate beats/min		Duration over readings min	Number of exposees
db/wb	mean	s.d	mean	mean	s.d	mean	mean	s.d.	mean	
37.0/30.0	111.0	23.2	5.5	156.0	22.4	1.3	45.0	11.6	233.3	4*
	125.0	11.8	8.5	166.0	12.0	4.5	41.0	10.9	157.0	4
37.8/31.9	123.8	15.3	11.7	187.0	23.4	1.3	63.2	25.2	107.0	18*
	135.7	18.4	9.5	211.3+	33.2+	0.7	75.7+	42.6+	70.2	6
46.0/29.5	134.7	13.2	14.5	198.9+	22.8+	2.5	64.2+	14.3+	102.8	11*
	130.2	12.5	12.0	220.6+	14.3+	4.5	90.5+	16.1+	80.0	13
54.3/28.2	126.0	14.5	8.2	200.0	7.4	0.8	74.0	28.4	111.0	5*
	130.0	18.0	6.7	211.6+	18.3+	2.8	81.6+	18.5+	54.8	19
37.5/33.9	110.5	12.0	5.9	181.5+	19.3+	1.9	71.2+	21.2+	79.2	31
54.5/29.8	129.6	14.6	7.1	220.7+	13.6+	3.7	91.3+	22.0+	54.8	24
38.0/35.3	106.7	12.2	3.1	182.9+	5.7+	1.4	76.2+	19.2+	47.3	31
60.0/30.0	137.1	11.7	7.8	219.2+	18.6+	2.2	81.6+	19.5+	36.7	24
43.0/35.0	123.0	6.2	8.5	178.0	6.8	1.5	55.0	22.6	46.8	8
40.0/36.7	108.8	11.8	4.4	181.1+	20.7+	1.3	71.7+	21.2+	33.4	31
48.6/35.0	133.7	14.4	7.4	222.3+	19.6+	1.8	89.1+	21.7+	40.1	24
60.0/32.5	131.7	14.1	5.5	224.1+	3.9+	2.3	92.4+	14.2+	36.0	24
50.0/37.0	131.0	3.8	8.0	172.8	15.1	4.3	41.8	5.7	27.0	8
45.0/41.0	109.3	14.6	3.1	182.8+	4.6+	1.3	73.5+	16.1+	21.9	31
53.0/40.0	131.0	10.8	5.1	189.3	17.5	1.9	58.3	15.2	14.4	8
65.8/37.5	134.8	13.8	4.3	222.1+	14.1+	1.7	87.3+	18.8+	21.3	24
56.0/43.0	114.8	12.9	2.4	178.8	18.4	1.4	64.0	15.7	12.3	8
71.5/42.5	141.0	16.6	3.1	212.8+	21.4+	1.7	71.8+	17.1+	13.5	24
53.0/48.3	126.6	19.9	2.5	184.2+	15.2+	0.6	57.6+	21.3+	9.0	31
63.0/47.0	130.3	13.6	2.4	182.3	16.3	0.8	52.0	21.3	7.8	8
83.4/41.2	142.7	12.1	2.6	220.5+	23.2+	1.0	77.6+	20.4+	11.4	21

* Exposures terminated before imminent heat collapse.

\+ Pulse rates too fast to count by palpation at the wrist included.

Body temperature: In the investigations on 8 and 31 men body temperature was assessed during exposures from an indwelling sub-lingual thermocouple. The investigations in which 24 subjects participated recorded external auditory meatal temperatures from indwelling thermistors. A summary of these data is given in Table 9. In the Table, it may be noticed that there was no consistent tendency for either the 'final' body temperature or the increase in body temperature to vary with climatic severity. As with the pulse rate data, the values shown in Table 9 are based upon those first recorded after entry into the hot chamber, those last recorded before the exposee was removed from the hot-chamber and the differences between two sets of values. It should be noted that one of the signs which observers watched for as an indication of the approach of heat collapse was a tendency to gasp for air. In those investigations in which sub-lingual temperature was monitored there may have been an influence on these values of the temperature of air inspired through the mouth in those exposees who were near collapse.

Table 9: Body (ear or mouth) temperature of men working continuously at about 310 J/sec during exposure to high temperature environments.

Climate °C db/wb	Initial temperature °C Mean	Initial temperature °C s.d	Time after entry min Mean	Final temperature °C Mean	Final temperature °C s.d	Time before collapse min Mean	Increase in temperature °C Mean	Increase in temperature °C s.d	Duration over readings min Mean	Ear (E) or Mouth (M) temp	Number of exposees
37.0/30.0	36.6	0.4	0.0	37.8	0.9	2.5	1.27	0.48	237.5	M	4*
	37.0	0.6	0.0	38.4	0.4	1.8	1.45	0.42	166.3	M	4
37.8/31.9	36.8	0.5	1.1	38.5	0.4	0.0	1.73	0.58	119.0	E	18*
	36.9	0.6	1.0	38.6	1.0	0.0	1.72	0.52	79.3	E	6
46.0/29.5	36.9	0.4	1.5	38.5	0.4	0.0	1.59	0.47	118.6	E	11*
	36.8	0.3	1.8	39.0	0.4	0.8	2.18	0.47	93.9	E	13
54.3/28.2	36.9	0.5	1.4	38.7	0.3	1.0	1.83	0.33	117.6	E	5*
	37.0	0.4	1.8	39.2	0.4	0.0	2.17	0.48	61.4	E	19
37.5/33.9	36.8	0.2	4.1	38.9	0.4	2.5	2.05	0.38	80.4	M	31
54.5/29.8	36.9	0.5	1.1	39.1	0.6	0.0	2.18	0.45	64.4	E	24
38.0/35.3	36.8	0.3	3.3	39.1	0.4	1.2	2.30	0.55	49.4	M	31
60.0/30.0	36.9	0.6	1.0	39.2	0.5	0.1	2.30	0.48	45.6	E	24
43.0/35.0	36.4	0.5	0.0	38.6	0.3	2.4	2.22	0.38	54.4	M	8
40.0/36.7	36.8	0.3	3.6	39.0	0.5	1.4	2.23	0.48	39.2	M	31
48.6/35.0	36.9	0.4	1.6	39.5	0.3	0.0	2.59	0.41	47.7	E	24
60.0/32.5	36.9	0.6	1.2	39.3	0.7	0.1	2.40	0.47	42.5	E	24

Climate °C db/wb	Initial temperature °C Mean	Initial temperature °C s.d	Time after entry min Mean	Final temperature °C Mean	Final temperature °C s.d	Time before collapse min Mean	Increase in temperature °C Mean	Increase in temperature °C s.d	Duration over readings min Mean	Ear (E) or Mouth (M) temp	Number of exposees
50.0/38.0	36.2	0.5	0.0	38.8	0.3	1.0	2.52	0.45	38.3	M	8
45.0/41.0	36.8	0.3	3.1	39.2	0.5	0.9	2.40	0.60	22.3	M	29
53.0/40.0	36.4	0.5	0.0	38.9	0.5	0.9	2.59	0.58	20.5	M	8
65.8/37.5	37.0	0.4	1.1	39.6	0.5	0.1	2.62	0.44	26.0	E	24
56.0/43.0	36.5	0.3	0.0	39.0	0.5	0.6	2.50	0.67	15.4	M	8
71.5/42.5	37.0	0.5	1.0	39.6	1.7	0.2	2.56	0.54	17.0	E	24
53.0/48.3	36.9	0.4	2.1	39.1	0.6	0.6	2.16	0.55	9.5	M	31
63.0/47.0	36.7	0.3	0.0	38.5	0.8	1.0	1.85	1.00	9.9	M	8
83.4/41.2	36.8	0.6	1.0	38.9	0.9	0.2	2.03	0.64	13.7	E	21

* Exposures terminated before imminent heat collapse.

Acclimatisation: At the beginning of each five day series of experiments subjects were unacclimatised to heat. Over the five days some acclimatisation could have occurred. The investigation was not designed to examine the effect of acclimatisation on tolerance times in hot conditions and for this reason the curves of predicted imminent collapse times are based upon data collected from a random order design of environments and occasions.

Some indication of the effects of occasion(or acclimatisation)is possible when the deviations from predicted mean imminent collapse times are examined on each of the five successive days. Not all climatic conditions appeared with equal frequency on all five days. In order, therefore, to see whether the random ordering of climates had been successful in minimising acclimatisation effects a plot was made of the environments which were employed on each day. These data are shown in the lower half of Figure V. From this Figure it is apparent that the mean environmental temperature, expressed in terms of the weighting found to be appropriate for the prediction of mean times imminent heat collapse, was not quite uniform over the five days. However, no tendency is apparent in these data for climatic severity to increase or decrease systematically over the five occasions on which observations were made.

The means of the deviations of individual times to imminent heat collapse from predicted values are shown in the upper half of Figure V. It can be seen that the mean value of the data collected on Day 1 tended to underestimate by about 5 min the predicted mean imminent collapse time for the environments employed on that day. This under-estimation was reduced to 0.2 min on Day 2 and on Days 3, 4 and 5 the observed data tended to slightly over-estimate the predicted times to imminent heat collapse in the climates studied to the extent of less than 2 min.

The relatively small magnitude of these differences would suggest that the curves of safe exposure times included in this report should be regarded as applicable to unacclimatised men. Adjustments to predicted safe exposure times to take account of the effects of full acclimatisation of exposees cannot be suggested on the basis of the data reported here.

Recovery from exposure: It was not the purpose of these investigations to examine the physiological dynamics of heat collapse. Nor was it the intention of the investigators to examine the course of recovery from heat exposure. However, after each man had attained a state of imminent heat collapse his pulse rate and oral (or ear) temperature were monitored until it was judged safe to allow the man to shower and leave the experimental area. A guide taken by observers in reaching a decision that a man could be released was the attainment of a steady level of temperature and pulse rate or levels comparable to those recorded during the pre-exposure period.

Mean times taken for recovery defined in this way have been calculated in respect of each of the twenty-one climatic conditions to which subjects had been exposed. These values are shown in Table 10. It may be seen in the Table that there was no apparent tendency for recovery time to be systematically related to climatic severity and that within the recovery periods following each climate there was considerable variation between subjects.

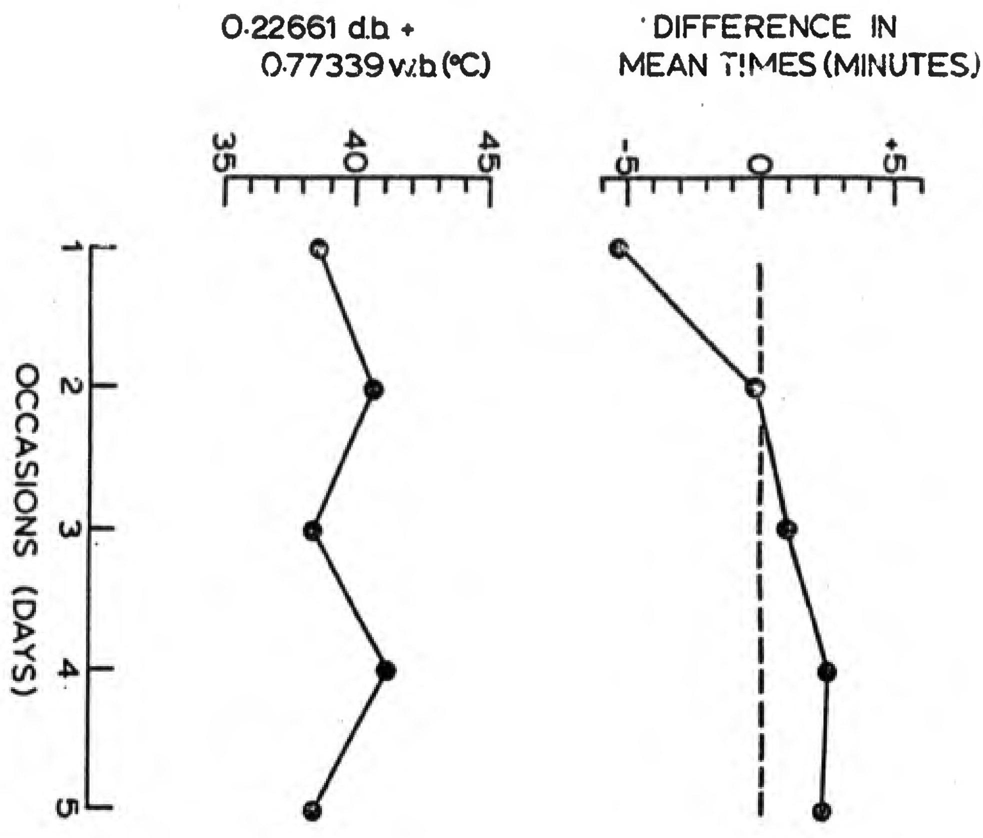


FIGURE V **Climates investigated and mean discrepancies between observed and predicted mean times to imminent heat collapse plotted against five experimental occasions (successive days).**

Table 10: Times to recover from imminent collapse during exposure to high temperature environments.

Climate db/wb ^{o}C	Time to recovery min Mean	s.d	N	95% Safe recovery time min
37.8/31.9	45.8	10.63	18*	64.3
	47.0	5.83	6	58.8
46.0/29.5	44.5	8.41	11*	59.7
	54.6	15.72	13	82.6
54.3/28.2	34.8	5.40	5*	46.3
	44.1	11.65	19	64.3
37.5/33.9	40.6	9.51	31	56.8
54.5/29.8	41.0	12.52	24	62.4
38.0/35.3	40.5	8.64	31	55.2
60.0/30.0	41.9	11.35	24	61.3
43.0/35.0	48.3	8.81	7	65.4
40.0/36.7	35.3	5.71	31	45.0
48.6/35.0	44.0	10.55	24	62.0
60.0/32.5	40.4	4.72	24	48.5
50.0/37.0	43.9	16.46	8	75.2
45.0/41.0	35.7	10.04	31	52.8
53.0/40.0	35.6	6.19	8	47.4
65.8/37.5	41.5	8.23	24	55.6
56.0/43.0	40.9	13.32	8	66.2
71.5/42.5	34.7	14.21	24	59.0
53.0/48.3	31.6	14.11	23	55.9
63.0/47.0	38.6	11.20	8	59.9
83.4/41.2	39.6	6.27	21	50.4

*Exposures terminated before imminent heat collapse.

No recovery time data were collected in the exposure of 8 men to the 37.0/30.0°C db/wb climate and several data were missing due to equipment failure in the periods of recovery to other climates to which other subjects had been exposed.

From all the occasions on which a recovery time was recorded following an exposure in which imminent heat collapse had occurred, an average recovery time of 40 min was found. Ninety-five per cent of all recovery times were of a duration of less than 58 min. This value together with the 95% safe recovery times shown in the Table were derived from an addition to the mean recovery time of the product of the unbiassed estimate of the standard deviation and the 90% 't' value appropriate to the number of subjects involved.

Recovery time was not defined in these investigations as a duration of rest in an environment at 22 ± 2°C which would permit re-exposure to a given environment for a duration comparable to that found on first exposure. The criterion of recovery employed here was a return of body temperature to either a pre-exposure level or to a steady level.

Observable signs of impending collapse: In other sections the pulse rates and temperatures of the exposees at the termination of exposures were described. Data of this kind were not, however, the only source of information used by observers in deciding to continue or to end an exposure for a particular exposee. Other, less quantifiable, factors were taken into account. Some of these have been mentioned in the list of criteria taken as guide-lines by the hot-chamber observers in their decision whether to end an exposure or not.

In the final investigations of this series, observers in the hot chamber were given the opportunity to comment on the exposees' condition. These remarks were written on proformae, which the observers had taken into the chamber with them, during the actual exposure of the man whose condition was being described.

A total ot 688 comments was found when the proformae were examined after the field work had been completed. These seemed to afford an opportunity for some statement to be made about the condition of the exposees as they neared collapse.

It is most important, however, that an acknowledgement be made of the nature of these data. The observers were not asked to make systematic recordings for subsequent analysis. The decision to examine their comments was made only after the investigations had been completed. Consequently the data reflect (a) the tendency for no comments to be made when observers were busy, rightly, with the welfare of an exposee, (b) an ambiguity consequent upon the absence of a previously-determined hierarchy of descriptive phrases, and (c) a predominance of complaints from exposees which were sometimes volunteered and sometimes elicited in response to a question about how the exposee was feeling.

Even with these limitations, however, the 688 comments could be examined in two ways. Firstly, a somewhat coarse grouping of comments was possible to see which data occurred most frequently. Secondly each comment could be placed in time and identified in terms of the proportion (%) of that individual exposee's exposure that had elapsed when the comment was made.

Fourteen groups of signs could be seen in the data in addition to one group of miscellaneous items most of which occurred only once on the proformae. Almost no observations were recorded before the exposures were at least half-way through. Within each group of signs the percentage frequency distribution was examined for each 10% of exposure duration. In an exposure lasting 20 min the final 10% category of the distribution occupied only 2 min and in an exposure lasting 80 min the final 10% category occupied the last 8 min before the exposure was terminated.

Observations were not evenly distributed between the fourteen groups of signs. Their apportionment is shown in Table 11.

Table 11: Distribution of comments on exposees' condition made by hot-chamber observers.

Observation	Number of observations	Percentage distribution of observation times					
		≤50	51-60	61-70	71-80	81-90	≥91%
Tired, weary, weak, "all-in", exhausted, "clapped", beaten.	146	0.8	2.7	3.4	17.8	26.0	49.3
Breathing difficulty, gasping, coughing, chest tightness or pain.	118	1.7	3.4	5.9	9.3	28.0	51.7
Feeling dizzy, giddy, light-headed, head swimming.	115	1.0	1.7	4.3	8.7	21.7	62.6
Rolling, swaying, skipping, erratic, unco-ordinated, staggering, stumbling.	78	-	-	5.1	-	12.8	82.1
Motivation gone- "had enough", "can't go on", "must get out".	40	-	-	-	5.0	22.5	72.5
Legs tired, weak, heavy, acheing, groggy.	36	2.6	5.6	13.9	16.7	30.6	30.6
Feeling sick, queasy, nausea, retching, desire to vomit.	29	-	-	6.9	10.3	20.7	62.1
Soreness in eyes, nose, lips, mouth or throat.	29	3.5	3.5	20.7	37.9	13.8	20.7
Feeling "rough"	25	-	-	4.0	12.0	48.0	36.0
Headache	23	4.3	-	8.7	8.7	39.1	39.1
Stomach-ache, cramp	13	7.7	7.7	-	23.1	38.5	23.1
'Pins and needles', tingling burning in extremities or skin	13	7.7	-	7.7	7.7	23.1	53.8
Confused, incoherent	11	-	-	9.1	9.1	9.1	72.7
Blurred or double vision, 'spots before the eyes'.	5	-	-	-	-	40.0	60.0
Others - haemorrhoids, heart-burn, backache, etc.	7	-	14.3	28.6	14.3	14.3	28.6
All Observations	688	1.3	2.2	6.0	11.6	24.6	54.4

Comments about the exposees' tiredness were made most frequently and comments about visual aberrations were made least frequently. In some groups the frequency of occurrence of the observations was spread fairly evenly over the last half or third of the exposures. Two examples of this feature are the 36 comments relating to tiredness in the legs and the 29 comments relating to complaints about soreness in the eyes, nose, mouth and throat of exposees. In other groups of observations the frequency distribution showed a rather marked and sudden increase as imminent heat collapse came near. Three groups which show this feature are the 78 comments about exposees loss of motor control on the stepping routine, the 40 comments reflecting a loss of the exposees' motivation to continue the exposure and the small number of comments that the exposee was mentally confused and incoherent.

This preliminary analysis of these unsystematically collected observations would seem to suggest that from a future investigation it might be possible to produce a practical guide to hot-chamber observers which would weight the signs of imminent heat collapse in accordance with their frequency of occurrence and their distribution over time within exposures. Such an analysis was not justified, however, on these data in view of the limitations on them which have been described.

IV DISCUSSION

The data presented in this report have permitted predictions to be made of the tolerance times to imminent heat collapse of young, fit, unacclimatised men exposed to high temperature environments. A general equation has been devised relating exposure times to a measure of environmental severity. However several factors serve to make difficult a comparison of the present findings and those reported in the literature. These factors serve to limit the generality of conclusions drawn from particular investigations of the responses of men working in heat.

Differences, which would affect extrapolations, have occurred between investigations in:- (i) the range and nature of the thermal environments chosen; (ii) the description of environmental severity found to be appropriate in relation to the exposees' responses studied; (iii) the criteria adopted as a basis for the termination of exposures; (iv) the activity levels of exposees during their stay in heat; (v) the degree of special training or acclimatisation afforded exposees before experimental runs were begun; and (vi) the type of population samples whose responses were studied.

For these reasons it has proved impossible to incorporate data published by other workers directly into the findings presented here. This was not the case in respect of the recommendations based upon the responses of seated exposees (Provins, Hellon, Bell and Hiorns, 1962; Bell, Hellon, Hiorns, Nicol and Provins, 1963). However some qualitative comparisons are possible between the results of the present investigations and the results of other research.

In the relationship of mean times to imminent heat collapse and thermal severity an asymptotic value of 30.55°C weighted temperature plus or minus 0.99°C was found. This suggests that the present data would indicate that in environments in the region of 29.5 to 31.5°C weighted temperature, exposees should be able to maintain their thermal equilibrium and avoid collapse.

Several authors have suggested limits of environmental severity for specified durations of exposure beyond which an increasing proportion of exposees would suffer heat collapse. Robinson, Turrell and Gerking (1945) found that acclimatised men wearing poplin uniforms could not maintain thermal equilibrium for 6 hours beyond environments of 32.0/31.5°C db/wb or 50.0/26.0°C db/wb when exposees worked at 220 J/m^2/sec and beyond environments of 34.0/33.5°C db/wb or 50.0/29.0°C db/wb when exposees worked at 150 J/m^2/sec. With specially acclimatised exposees in Naval drill uniforms Ellis, Ferres, Lind and Newling (1953) found that an average work rate of 115 J/m^2/sec over 4 hr "when the air temperature was 100°F (37.8°C) or less the wet-bulb temperature above which some men were incapacitated was 92°F (33.3°C)".

Lind (1963) has suggested that environments of 30.2°C and 27.4°C Effective Temperature are the limits of severity for daily exposure of unacclimatised men working at 115 and 175 J/m^2/sec respectively, whilst for acclimatised men working at similar rates in saturated environments, Wyndham, Bouwer, Devine and Paterson (1953) have suggested limiting wet-bulb temperatures of 32.2°C and 30.6°C.

For men working at an average energy expenditure of 130 J/m^2/sec studies reported by Adam, Collins, Ellis, Irwin, Jack, John, Jones, MacPherson and Weiner (1955) have suggested that the limit of 4 hr exposures is reached at a wet-bulb temperature of 31.1°C for especially acclimatised men and at a wet-bulb temperature of 28.3°C for men naturally acclimatised to the tropics when the dry-bulb temperature is 48.9°C.

The range of these values reflects not only differences in work rates, degrees of acclimatisation of exposees and durations of time over which the maintenance of thermal equilibrium is predicted but also the criteria adopted in identifying collapse or the loss of equilibrium. In the present studies the asymptotic value represents environments in which the state of imminent heat collapse would be unlikely to occur. This state was identified by the experienced observers who noted the signs described in Table 11 above and who took cognisance of the pulse rates and body temperatures shown in Tables 8 and 9 above.

Similar signs of impending heat collapse have been described by Eichna, Ashe, Bean and Shelley (1945) who noted the occurrence in their investigations of physically-fit acclimatised men working at rates of 155-185 J/m^2/sec the "frequent complaints of violent throbbing headache, dizziness, marked fatigue with inability to keep the pace, difficulty in breathing, coronary type of precordial pain and substernal distress, abdominal cramps and nausea". Their 13 exposees all completed 4 hr continuous work in the 8 db/wb environments of 33.7/33.6; 34.1/33.4; 34.5/33.4; 44.2/31.9; 49.2/32.1; 34.4/34.4; 38.2/33.9 and 41.3/33.6°C. Not all their exposees were able to complete the 4 hr work period in the six db/wb climates of 37.8/34.6; 48.5/33.2; 35.6/35.5; 37.6/35.6; 41.2/35.0 and 48.8/34.4°C.

Weiner (1938) in a study of naturally acclimatised Bantu mine workers engaged in a shovelling task followed by a period of standing upright found that in those exposees about to collapse "the first signs were bending forward of the head, closing of the eyes, sighing, tonelessness and restlessness of the body and a request to be allowed to lean or sit down. The symptoms which fainting subjects experienced were lassitude, weakness, nausea, giddiness and a period of blackness".

Ellis, Ferres, Lind and Newling (1953) have described "the incapacitation of those who were not able to complete their tasks" in terms of "symptoms of dizziness, lightheadedness, sluggish mentality, blurred vision, 'pins and needles' in the extremities, headache, abdominal discomfort, nausea or vomiting, or acute 'hot-climate' fatigue, with complete inability to continue working". The authors also noted in their incapacitated exposees that "their step-climbing became less rhythmical....they stumbled....they paid little attention to the observers, occasionally threw their arms about, and eventually refused, or were unable, to go on". Finally, in these investigations it was reported that "irritability was frequent, and outbursts of bad temper or emotional weeping were not uncommon, when men were nearing the limit of their endurance".

Most investigations of the tolerance of working men in high temperature environments have employed a combination of indices of actual, or approaching, distress of exposees. Ellis, Ferres, Lind and Newling (1953), for example, cite seven criteria used by hot chamber observers in their studies of intermittent work at high temperatures. These are (i) pulse rate of over 160/min after work, (ii) pulse rate of over 140/min before work, (iii) rectal temperature of 39.2°C or higher, (iv) rise in pulse rate during rest, (v) definite signs of physical inability to cope with the task, (vi) evident cyanosis or circumoral pallor, and (vii) any complaints of unpleasant symptoms, e.g. faintness or cramp etc. Wyndham, Williams, Morrison and Heyns (1967) in their studies of continuous work at high temperatures of acclimatised Bantu mine workers judged "the limit of tolerance to heat.... on one or other of the following three criteria: (a) a rectal temperature of 40.0°C; (b) repeated collapse over a short period of time; or (c) uncontrollable behaviour, such as aggression or hysteria". In another publication Wyndham and his colleagues (Wyndham, Strydom, Morrison, Williams, Bredell, Maritz and Munro, 1965) suggested that "although an individual may experience difficulty in completing a task when his rectal temperature exceed 38.3°C, he is not at the point at which excessive or intolerable conditions occur, with a danger of rectal temperature rising to hyperpyrexial levels, until his thermoregulatory processes are saturated or reach their maximum values. This does not happen until rectal temperatures reach 38.9-39.4°C.".

Among the exposees who collapsed in the investigations of Eichna, Ashe, Bean and Shelley (1945) "usually the rectal temperatures were over 38.9°C, and the heart rates exceeded 150 per minute". Wyndham and Williams (1967) have described rectal temperatures of more than 39.2°C as "the upper limit for men working with difficulty". Lofstedt (1966) found for 55 male and female, seated or working exposees to high temperature conditions that "about 66% of exposees had reached their endurance limit at a rectal temperature of 39.2°C". Dukes-Dubos and Lofstedt (1967) in a study of exposees working at 185 $J/m^2/sec$ recorded their times to attain a rectal temperature of 39.2°C and found that two in six had reached this level in less than a 3 hr exposure to 32.8/31.1°C db/wb and that none in six had reached this level in less than a 3 hr exposure to 30.0/26.7°C db/wb.

In a study of exposees working at a rate of 200 $J/m^2/sec$ during exposure to environments with effective temperatures in the range 25.5 to 32.5°C Williams and Wyndham (1967) withdrew their subjects from heat when rectal temperatures had reached 39°C or heart rate had reached 180 beats/min.

The variation between the levels of rectal temperature or pulse rate chosen as withdrawal, distress, or impending collapse criteria is a reflection of the variation in the purposes of the studies in which these criteria are employed. Lind, Weiner, Hellon, Jones and Frazer (1957) illustrate this point with reference to their own study when they comment that "the establishment of a physiological criterion for withdrawal of subjects from the heat presents some difficulties. Though it would provide the most realistic criterion, it was clearly inadvisable to induce a state of collapse, or even of incipient collapse, in men who undergo successive exposures. We decided that withdrawal of the subjects when their rectal temperatures reached 38.8°C as nearly as experimental conditions would allow, would indicate a similarity of physiological strain and one of undoubted severity. .... Perhaps the achievement of a fixed rectal temperature increment might have been a better method, but practical difficulties discouraged its use". For exposees working at an average rate of 230 $J/m^2/sec$ these authors "expected five minutes grace between the achievement of a rectal temperature of 38.8°C and a state of incipient collapse" in the environmental conditions they employed.

A problem in the adoption of physiological criteria like rectal temperature or pulse rate, or indeed in the adoption of more clinical, observable, criteria, is the difficulty in allowing for variation between exposees. This variation appears to result not only from fairly gross influences like work rate or acclimatisation but also from more subtle, and less readily identified and quantifiable, influences possibly related to differences between exposees in their cardiovascular lability, the sensitivity of their peripheral and hypothalamic temperature receptors and the attitude to the experimental situation of each exposee.

Attempts were made in the most recent, as in previous, parts of this investigation to find predictor variables which would enable the potentially heat-intolerant individuals to be identified before they were exposed to heat. This exercise produced nothing of value in this respect. It is cold comfort that other investigators, where any attention at all appears to have been paid to the question of variation between individuals, have had little success in the identification of influential personal characteristics. Ellis, Ferres, Lind and Newling (1953) considered this problem but "were left with the firm conviction that none of the methods available at the present time for predicting the probability of survival under extremely warm conditions are satisfactory. The only way to determine with confidence how men will react is to expose them to the conditions in question and see what happens. We failed repeatedly to forecast whether or not men could collapse in this series!".

The description of climatic severity found statistically to be most appropriate in relation to the tolerance time data in this series of investigations was 0.22661 dry bulb + 0.77339 wet bulb temperature in °C. Because this weighting was produced specifically in the context of the present data it has not appeared elsewhere in the literature. With relatively mild levels of warmth previous investigators have found that the Effective Temperature Scales developed by Houghten and Yagloglou (1923) and others on the basis of Carrier's (1911) psychometric charts have served as a useful basis for the description of environmental variables. At levels of heat stress beyond those at which the accuracy of the Effective Temperature scales is acceptable, the Predicted Four-Hour Sweat Rate (McArdle, Dunham, Holling, Ladell, Scott and Weiner, 1947; Weiner, 1948) has provided a means whereby the conditions in which heat exposure takes place may be described. The P4SR, however, as its name implies was based upon exposees' responses in conditions of thermal severity which could be tolerated for 4 hr.

In conditions more severe still there is no generally accepted, or universally appropriate, index of environmental severity. Although in the present study a weighting of 0.22661 dry bulb + 0.77339 wet bulb temperature in °C provided the most satisfactory description of environmental severity, it is not possible to state that this, or any other weighting previously used, will be most appropriate for all studies of the tolerance times of men exposed to high temperature conditions. The pertinent features of their investigations which made an appropriate weighting of 0.2 db + 0.8 wb in the study of Bidlot and Ledent (1947); 0.1 db + 0.9 wb in the study by Houberechts, Lavenne and Patigny (1958); 0.15 db + 0.85 wb in the studies by Lind (1963) and his colleagues (Lind, Weiner, Hellon and Jones, 1955; Lind, Weiner, Hellon, Jones and Frazer, 1957) or 0.3 db + 0.7 wb in the study by Bell and Walters (1969) are as yet unidentified. It may be that differences in work rate or in levels of environmental humidity made significant contributions. At present, however, this problem is unresolved. It should be possible, at least in principle, to devise a tolerance to heat nomogram which would incorporate work rate, clothing, degree of acclimatisation of exposees and the dry-bulb, wet-bulb, globe temperatures and air movements of the environments. This could only be attempted, however, when considerably more empirical data have been collected.

Finally, it has been the aim of the present investigation to produce recommendations of safe exposure times for specified proportions of young, fit men exposed to high temperature conditions. Almost all studies reported in the literature have been designed to produce information highly specific to the particular concerns of their authors. Thus some reports have sought to establish limits of thermal equilibrium for "average" exposees. Others have established mean tolerance times for groups of exposees. Rarely have studies been described in which the aim of the investigation was to establish a range of safe exposure times similar to those desired here.

Lind, Weiner, Hellon, Jones and Frazer (1957) however have proposed that the protection of heat intolerant individuals in their study could be achieved by taking the value of the lower 90% confidence limit on mean tolerance times and subtracting from it a further 10 min. Iampietro and Goldman (1965) employed the mean tolerance times of the first five of ten men who collapsed in the hot environments they studied. Leithead and Lind (1964) have suggested that "safe tolerance times should be taken to be 75% of the average times" to collapse in heat. In the present investigation safe exposure times have been described for several proportions of exposees, similar to those studied here, who are required to work at about 310 J/sec in environments of the severity described in Table 2 above.

V CONCLUSION

From observations of the times taken to reach a state of imminent heat collapse in young, fit, unacclimatised men dressed in denim overalls, underpants, socks and shoes, and working continuously at 310 J/sec in 21 high temperature environments, it has been possible to describe a rectangular hyperbolic curve relating heat tolerance to environmental severity. By taking into account the differences between individuals in their relative tolerance-intolerance of heat, safe exposure times have been calculated which should permit 75%, 80%, 90% or 99% of exposees to avoid reaching a state of imminent heat collapse.

These findings express general relationships which should obtain in all situations which could be said to have been represented by the conditions of the present investigations.

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Note. Reports quoted are not necessarily available to the public or to commercial organisations.

ANNEX

Table A: 50% safe exposure times (in minutes) for unacclimatised young fit exposees dressed in overalls and working continuously at 310 J/sec in air movements of 0.76 or 1.02 m/sec.

Table B: 75% safe exposure times (in minutes) for unacclimatised young fit exposees dressed in overalls and working continuously at 310 J/sec in air movements of 0.76 or 1.02 m/sec.

Table C: 80% safe exposure times (in minutes) for unacclimatised young fit exposees dressed in overalls and working continuously at 310 J/sec in air movements of 0.76 or 1.02 m/sec.

Table D: 90% safe exposure times (in minutes) for unacclimatised young fit exposees dressed in overalls and working continuously at 310 J/sec in air movements of 0.76 or 1.02 m/sec.

Table E: 95% safe exposure times (in minutes) for unacclimatised young fit exposees dressed in overalls and working continuously at 310 J/sec in air movements of 0.76 or 1.02 m/sec.

Table F: 99% safe exposure times (in minutes) for unacclimatised young fit exposees dressed in overalls and working continuously at 310 J/sec in air movements of 0.76 or 1.02 m/sec.

Table A: **50% safe exposure times (in minutes) for unacclimatised fit, young exposees clothed in overalls and working at 310 J/sec in air movements of 0.76 or 1.02 m/sec.**

DRY BULB °C \ WET BULB °C	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
32	+	+	+	+	+	+																		
33	+	+	+	+	+	+	+																	
34	+	+	+	+	+	+	112	87																
35	+	+	+	+	+	+	104	82	67															
36	+	+	+	+	+	+	96	77	64	55														
37	+	+	+	+	+	116	89	73	61	53	46													
38	+	+	+	+	+	107	84	69	58	51	45	40												
39	+	+	+	+	+	99	79	65	56	49	43	39	35											
40	+	+	+	+	+	92	74	62	54	47	42	36	34	32										
41	+	+	+	+	111	86	70	60	52	45	41	37	33	31	28									
42	+	+	+	+	102	81	67	57	50	44	39	36	33	30	28	26								
43	+	+	+	+	95	76	64	55	48	42	38	35	32	29	27	25	24							
44	+	+	+	115	88	72	61	52	46	41	37	34	31	29	27	25	23	22						
45	+	+	+	105	83	68	58	50	45	40	36	33	30	28	26	24	23	22	20					
46	+	+	+	98	78	65	56	49	43	39	35	32	30	28	26	24	23	21	20	19				
47	+	+	119	91	74	62	53	47	42	38	34	31	29	27	25	24	22	21	20	19	18			
48	+	+	109	86	70	59	51	45	40	37	33	31	28	26	25	23	22	21	20	19	18	17		
49	+	+	101	80	66	57	49	44	39	36	32	30	28	26	24	23	21	20	19	18	17	17	16	
50	+	+	94	75	63	54	47	42	38	35	32	29	27	25	24	22	21	20	19	18	17	16	16	15
51	+	113	87	71	60	52	46	41	37	34	31	29	27	25	23	22	21	20	19	18	17	16	16	15
52	+	104	82	68	58	50	44	40	36	33	30	28	26	24	23	22	20	19	18	13	17	16	15	15
53	+	96	77	64	55	48	43	39	35	32	30	27	26	24	22	21	20	19	18	17	17	16	15	15
54	117	90	73	61	53	46	41	37	34	31	29	27	25	23	22	21	20	19	18	17	16	16	15	-
55	108	84	69	59	51	45	40	36	33	31	28	26	25	23	22	21	19	19	18	17	16	15	15	-
56	99	79	66	56	49	43	39	35	32	30	28	26	24	23	21	20	19	18	17	17	16	15	15	-
57		75	63	54	47	42	38	34	32	29	27	25	24	22	21	20	19	18	17	16	16	15	-	-
58			60	52	46	41	37	34	31	29	27	25	23	22	21	20	19	18	17	16	16	15	-	-
59			57	50	44	39	36	33	30	28	26	24	23	22	20	19	18	17	17	16	15	15	-	-
60				48	43	38	35	32	29	27	25	24	22	21	20	19	18	17	16	16	15	15	-	-
61				46	41	37	34	31	29	27	25	23	22	21	20	19	18	17	16	16	15	-	-	-
62					40	36	33	30	28	26	24	23	22	20	19	18	18	17	16	15	15	-	-	-
63					39	35	32	30	28	26	24	23	21	20	19	18	17	17	16	15	15	-	-	-
64						34	31	29	27	25	24	22	21	20	19	18	17	16	16	15	-	-	-	-
65						33	31	28	26	25	23	22	21	20	19	18	17	16	15	15	-	-	-	-
66							30	28	26	24	23	21	20	19	18	17	17	16	15	15	-	-	-	-
67							29	27	25	24	22	21	20	19	18	17	16	16	15	15	-	-	-	-
68								27	25	23	22	21	20	19	18	17	16	16	15	-	-	-	-	-
69									24	23	22	20	19	18	18	17	16	15	15	-	-	-	-	-
70									24	23	21	20	19	18	17	17	16	15	15	-	-	-	-	-
71										22	21	20	19	18	17	16	16	15	-	-	-	-	-	-
72										22	21	19	19	18	17	16	15	15	-	-	-	-	-	-
73											20	19	18	17	17	16	15	15	-	-	-	-	-	-
74											20	19	18	17	16	16	15	-	-	-	-	-	-	-
75												19	18	17	16	16	15	-	-	-	-	-	-	-
76												18	18	17	16	15	15	-	-	-	-	-	-	-
77													17	16	16	15	15	-	-	-	-	-	-	-
78													17	16	16	15	-	-	-	-	-	-	-	-
79														16	15	15	-	-	-	-	-	-	-	-
80														16	15	15	-	-	-	-	-	-	-	-
81															15	-	-	-	-	-	-	-	-	-
82																-	-	-	-	-	-	-	-	-
83																-	-	-	-	-	-	-	-	-
84																	-	-	-	-	-	-	-	-
85																	-	-	-	-	-	-	-	-

(Lower-left region of the table:) LESS THAN 10% RELATIVE HUMIDITY

+ Safe exposure for 120_+ minutes and longer towards top-left of the Table.

- Safe exposure for less than 15 minutes and shorter towards bottom-right of the Table.

Table B: 75% safe exposure times (in minutes) for unacclimatised fit, young exposees clothed in overalls and working at 310 J/sec in air movements of 0.76 or 1.02 m/sec.

WET BULB °C

DRY BULB °C	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
32	+	+	+	+	+	+																		
33	+	+	+	+	+	+	102																	
34	+	+	+	+	+	+	93	72																
35	+	+	+	+	+	117	86	68	56															
36	+	+	+	+	+	106	80	64	54	46														
37	+	+	+	+	+	97	75	61	51	44	39													
38	+	+	+	+	+	89	70	57	49	42	37	34												
39	+	+	+	+	110	82	66	55	47	41	36	33	30											
40	+	+	+	+	100	77	62	52	45	39	35	32	29	26										
41	+	+	+	+	92	72	59	50	43	38	34	31	28	26	24									
42	+	+	+	115	85	67	56	48	41	37	33	30	27	25	23	22								
43	+	+	+	104	79	63	53	46	40	36	32	29	27	25	23	21	20							
44	+	+	+	95	74	60	51	44	39	34	31	28	26	24	22	21	20	19						
45	+	+	120	88	69	57	48	42	37	33	30	28	26	24	22	21	19	18	17					
46	+	+	108	81	65	54	46	41	36	32	29	27	25	23	22	20	19	18	17	16				
47	+	+	99	76	61	52	45	39	35	32	29	26	24	23	21	20	19	18	17	16	15			
48	+	+	91	71	58	49	43	38	34	31	28	26	24	22	21	20	18	17	17	16	15	14		
49	+	113	84	67	55	47	41	37	33	30	27	25	23	22	20	19	18	17	16	15	15	14	14	
50	+	103	78	63	53	45	40	35	32	29	27	25	23	21	20	19	18	17	16	15	15	14	13	13
51	+	94	73	59	50	43	38	34	31	28	26	24	22	21	20	19	18	17	16	15	14	14	13	13
52	118	87	68	56	48	42	37	33	30	28	25	24	22	21	19	18	17	16	16	15	14	14	13	13
53	106	80	64	54	46	40	36	32	29	27	25	23	22	20	19	18	17	16	15	15	14	13	13	12
54	97	75	61	51	44	39	35	31	29	26	24	23	21	20	19	18	17	16	15	14	14	13	13	12
55	89	70	58	49	43	38	34	30	28	26	24	22	21	19	18	17	16	16	15	14	14	13	13	12
56	83	66	55	47	41	36	33	30	27	25	23	22	20	19	18	17	16	15	15	14	14	13	12	12
57		62	52	45	40	35	32	29	27	25	23	21	20	19	18	17	16	15	15	14	13	13	12	12
58			50	43	38	34	31	28	26	24	22	21	20	18	17	17	16	15	14	14	13	13	12	12
59			48	42	37	33	30	27	25	23	22	20	19	18	17	16	16	15	14	14	13	13	12	12
60				40	36	32	29	27	25	23	21	20	19	18	17	16	15	15	14	13	13	12	12	11
61				39	35	31	28	26	24	23	21	20	19	18	17	16	15	14	14	13	13	12	12	11
62					33	30	28	26	24	22	21	19	18	17	16	16	15	14	14	13	13	12	12	11
63					32	30	27	25	23	22	20	19	18	17	16	15	15	14	13	13	12	12	12	11
64						29	26	24	23	21	20	19	18	17	16	15	15	14	13	13	12	12	11	11
65						28	26	24	22	21	20	18	17	17	16	15	14	14	13	13	12	12	11	11
66							25	23	22	20	19	18	17	16	16	15	14	14	13	12	12	12	11	11
67							25	23	21	20	19	18	17	16	15	15	14	13	13	12	12	11	11	11
68								22	21	20	19	18	17	16	15	14	14	13	13	12	12	11	11	11
69									21	19	18	17	16	16	15	14	14	13	13	12	12	11	11	11
70									20	19	18	17	16	15	15	14	13	13	12	12	12	11	11	10
71										19	18	17	16	15	14	14	13	13	12	12	11	11	11	10
72										18	17	16	16	15	14	14	13	13	12	12	11	11	11	10
73											17	16	15	15	14	14	13	12	12	12	11	11	10	10
74											17	16	15	15	14	13	13	12	12	11	11	11	10	10
75												16	15	14	14	13	13	12	12	11	11	11	10	10
76												16	15	14	14	13	13	12	12	11	11	10	10	-
77													15	14	13	13	12	12	12	11	11	10	10	-
78													14	14	13	13	12	12	11	11	11	10	10	-
79														14	13	13	12	12	11	11	11	10	-	-
80														13	13	12	12	12	11	11	10	10	-	-
81															13	12	12	11	11	11	10	10	-	-
82																12	12	11	11	11	10	10	-	-
83																12	12	11	11	10	10	-	-	-
84																	11	11	11	10	10	-	-	-
85																	11	11	11	10	10	-	-	-

LESS THAN 10% RELATIVE HUMIDITY

\+ Safe exposure for 120+ minutes and longer towards top-left of the Table.

\- Safe exposure for less than 10 minutes and shorter towards bottom-right of the Table.

Table C: 80% safe exposure times (in minutes) for unacclimatised fit, young exposees clothed in overalls and working at 310J/sec in air movements of 0.76 or 1.02 m/sec.

WET BULB °C

DRY BULB °C	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
32	+	+	+	+	+	+																		
33	+	+	+	+	+	+	97																	
34	+	+	+	+	+	+	89	69																
35	+	+	+	+	+	112	82	65	54															
36	+	+	+	+	+	101	76	61	51	44														
37	+	+	+	+	+	92	71	58	49	42	37													
38	+	+	+	+	117	85	67	55	47	40	36	32												
39	+	+	+	+	105	79	63	52	45	39	35	31	28											
40	+	+	+	+	96	73	59	50	43	38	34	30	28	25										
41	+	+	+	+	88	68	56	47	41	36	32	29	27	25	23									
42	+	+	+	110	81	64	53	45	40	35	31	29	26	24	22	21								
43	+	+	+	100	75	61	51	44	38	34	31	28	26	24	22	20	19							
44	+	+	+	91	70	57	48	42	37	33	30	27	25	23	21	20	19	18						
45	+	+	115	84	66	54	46	40	36	32	29	26	24	23	21	20	18	17	17					
46	+	+	104	78	62	52	44	39	34	31	28	26	24	22	21	19	18	17	16	15				
47	+	+	94	72	59	49	42	37	33	30	27	25	23	22	20	19	18	17	16	15	14			
48	+	120	87	68	56	47	41	36	32	29	27	25	23	21	20	19	18	17	16	15	14	14		
49	+	108	80	64	53	45	39	35	31	28	26	24	22	21	19	18	17	16	16	15	14	13	13	
50	+	98	74	60	50	43	38	34	30	28	25	23	22	20	19	18	17	16	15	15	14	13	13	12
51	+	90	69	57	48	42	37	33	30	27	25	23	21	20	19	18	17	16	15	14	14	13	13	12
52	112	83	65	54	46	40	35	32	29	26	24	22	21	20	18	17	16	16	15	14	14	13	12	12
53	102	77	61	51	44	38	34	31	28	26	24	22	21	19	18	17	16	15	15	14	13	13	12	12
54	93	71	58	49	42	37	33	30	27	25	23	22	20	19	18	17	16	15	14	14	13	13	12	12
55	85	67	55	47	41	36	32	29	27	24	23	21	20	19	18	17	16	15	14	14	13	13	12	12
56	79	63	52	45	39	35	31	28	26	24	22	21	19	18	17	16	15	15	14	13	13	12	12	11
57		59	50	43	38	34	30	28	25	23	22	20	19	18	17	16	15	15	14	13	13	12	12	11
58			48	41	36	33	29	27	25	23	21	20	19	18	17	16	15	15	14	13	13	12	12	11
59			45	40	35	32	29	26	24	22	21	20	18	17	16	16	15	14	14	13	13	12	12	11
60				38	34	31	28	26	24	22	20	19	18	17	16	15	15	14	13	13	12	12	11	11
61				37	33	30	27	25	23	21	20	19	18	17	16	15	14	14	13	13	12	12	11	11
62					32	29	26	24	23	21	20	19	17	17	16	15	14	14	13	13	12	12	11	11
63					31	28	26	24	22	21	19	18	17	16	15	15	14	13	13	12	12	12	11	11
64						27	25	23	22	20	19	18	17	16	15	15	14	13	13	12	12	11	11	11
65						27	25	23	21	20	19	18	17	16	15	[illegible]	14	13	13	12	12	11	11	11
66							24	22	21	19	18	17	16	16	15	14	13	13	12	12	11	11	11	10
67							24	22	20	19	18	17	16	15	15	14	13	13	12	12	11	11	11	10
68								21	20	19	18	17	16	15	14	14	13	13	12	12	11	11	10	10
69									20	18	17	16	16	15	14	14	13	12	12	12	11	11	10	10
70									19	18	17	16	15	15	14	13	13	12	12	11	11	11	10	10
71										18	17	16	15	14	14	13	13	12	12	11	11	11	10	-
72										18	17	16	15	14	14	13	13	12	12	11	11	10	10	-
73											16	16	15	14	13	13	12	12	11	11	11	10	10	-
74											16	15	15	14	13	13	12	12	11	11	11	10	-	-
75												15	14	14	13	13	12	12	11	11	10	10	-	-
76												15	14	14	13	12	12	12	11	11	10	10	-	-
77													14	13	13	12	12	11	11	11	10	10	-	-
78													14	13	13	12	12	11	11	10	10	-	-	-
79														13	13	12	12	11	11	10	10	-	-	-
80														13	12	12	11	11	11	10	10	-	-	-
81															12	12	11	11	11	10	-	-	-	-
82																12	11	11	10	10	-	-	-	-
83																11	11	11	10	10	-	-	-	-
84																	11	11	10	-	-	-	-	-
85																	11	10	10	-	-	-	-	-

LESS THAN 10% RELATIVE HUMIDITY

WET BULB °C

+ Safe exposure for 120+ minutes and longer towards top-left of the Table.
- Safe exposure for less than 10 minutes and shorter towards bottom-right of the Table.

Table D: 90% safe exposure times (in minutes) for unacclimatised fit, young exposees clothed in overalls and working at 310 J/sec in air movements of 0.76 or 1.02 m/sec.

DRY BULB °C \ WET BULB °C	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
32	+	+	+	+	+	+																		
33	+	+	+	+	+	+	86																	
34	+	+	+	+	+	111	79	61																
35	+	+	+	+	+	99	73	57	47															
36	+	+	+	+	+	90	67	54	45	39														
37	+	+	+	+	116	82	63	51	43	37	33													
38	+	+	+	+	104	75	59	49	41	36	32	28												
39	+	+	+	+	93	70	55	46	39	34	31	28	25											
40	+	+	+	+	85	65	52	44	38	33	30	27	24	22										
41	+	+	+	109	78	61	50	42	36	32	29	26	24	22	20									
42	+	+	+	97	72	57	47	40	35	31	28	25	23	21	20	18								
43	+	+	+	88	67	54	45	39	34	30	27	25	23	21	19	18	17							
44	+	+	114	81	62	51	43	37	33	29	26	24	22	20	19	18	17	16						
45	+	+	102	74	58	48	41	36	31	28	26	23	22	20	19	17	16	15	15					
46	+	+	92	69	55	46	39	34	30	27	25	23	21	20	18	17	16	15	14	14				
47	+	120	83	64	52	44	38	33	29	27	24	22	21	19	18	17	16	15	14	13	13			
48	+	106	77	60	49	42	36	32	29	26	24	22	20	19	18	16	16	15	14	13	13	12		
49	+	95	71	56	47	40	35	31	28	25	23	21	20	18	17	16	15	14	14	13	12	12	11	
50	+	87	66	53	44	38	34	30	27	25	22	21	19	18	17	16	15	14	14	13	12	12	11	11
51	111	79	61	50	42	37	32	29	26	24	22	20	19	18	17	16	15	14	13	13	12	12	11	11
52	99	73	58	48	41	35	31	28	25	23	21	20	19	17	16	15	15	14	13	13	12	11	11	11
53	90	68	54	45	39	34	30	27	25	23	21	19	18	17	16	15	14	14	13	12	12	11	11	10
54	82	63	51	43	37	33	29	26	24	22	21	19	18	17	15	15	14	13	13	12	12	11	11	10
55	75	59	49	41	36	32	28	26	24	22	20	19	17	16	15	15	14	13	13	12	12	11	11	10
56	70	56	46	40	35	31	28	25	23	21	20	18	17	16	15	14	14	13	12	12	11	11	11	10
57		52	44	38	33	30	27	24	22	21	19	18	17	16	15	14	14	13	12	12	11	11	10	10
58			42	36	32	29	26	24	22	20	19	18	17	16	15	14	13	13	12	12	11	11	10	10
59			40	35	31	28	25	23	21	20	18	17	16	15	15	14	13	13	12	11	11	11	10	-
60				34	30	27	25	23	21	19	18	17	16	15	14	14	13	12	12	11	11	10	10	-
61				33	29	26	24	22	20	19	18	17	16	15	14	13	13	12	12	11	11	10	10	-
62					28	26	23	22	20	19	17	16	15	15	14	13	13	12	12	11	11	10	-	-
63					27	25	23	21	20	18	17	16	15	14	14	13	12	12	11	11	11	10	-	-
64						24	22	21	19	18	17	16	15	14	13	13	12	12	11	11	10	10	-	-
65						24	22	20	19	18	17	16	15	14	13	13	12	12	11	11	10	-	-	-
66							21	20	18	17	16	15	14	14	13	12	12	11	11	11	10	-	-	-
67							21	19	18	17	16	15	14	14	13	12	12	11	11	10	10	-	-	-
68								19	18	17	16	15	14	13	13	12	12	11	11	10	10	-	-	-
69									17	16	15	15	14	13	13	12	11	11	11	10	-	-	-	-
70									17	16	15	14	14	13	12	12	11	11	10	10	-	-	-	-
71										16	15	14	13	13	12	12	11	11	10	10	-	-	-	-
72										16	15	14	13	13	12	12	11	11	10	-	-	-	-	-
73											14	14	13	12	12	11	11	11	10	-	-	-	-	-
74											14	14	13	12	12	11	11	10	10	-	-	-	-	-
75												13	13	12	12	11	11	10	10	-	-	-	-	-
76												13	13	12	11	11	11	10	-	-	-	-	-	-
77													12	12	11	11	10	10	-	-	-	-	-	-
78													12	12	11	11	10	10	-	-	-	-	-	-
79														12	11	11	10	-	-	-	-	-	-	-
80														11	11	11	10	-	-	-	-	-	-	-
81															11	10	10	-	-	-	-	-	-	-
82																10	10	-	-	-	-	-	-	-
83																10	-	-	-	-	-	-	-	-
84																		-	-	-	-	-	-	-
85																		-	-	-	-	-	-	-

(Lower-left region of table:) LESS THAN 10% RELATIVE HUMIDITY

\+ Safe exposure for 120+ minutes and longer towards top-left of the Table.
\- Safe exposure for less than 10 minutes and shorter towards bottom-right of the Table.

Table E: 95% safe exposure times (in minutes) for unacclimatised fit, young exposees clothed in overalls and working at 310 J/sec in air movements of 0.76 or 1.02 m/sec.

DRY BULB °C \ WET BULB °C	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
32	+	+	+	+	+	+																		
33	+	+	+	+	+	113	78																	
34	+	+	+	+	+	100	71	55																
35	+	+	+	+	+	89	66	52	43															
36	+	+	+	+	[illegible]	81	61	49	41	35														
37	+	+	+	+	105	74	57	46	39	34	30													
38	+	+	+	+	94	68	53	44	37	32	29	26												
39	+	+	+	+	84	63	50	42	36	31	28	25	23											
40	+	+	+	111	77	59	47	40	34	30	27	24	22	20										
41	+	+	+	98	70	55	45	38	33	29	26	24	21	20	18									
42	+	+	+	88	65	51	43	36	32	28	25	23	21	19	18	17								
43	+	+	117	80	60	49	41	35	31	27	24	22	20	19	18	16	15							
44	+	+	103	73	56	46	39	33	29	26	24	22	20	18	17	16	15	14						
45	+	+	92	67	53	44	37	32	28	26	23	21	19	18	17	16	15	14	13					
46	+	+	83	62	50	41	35	31	28	25	23	21	19	18	16	15	15	14	13	12				
47	+	108	75	58	47	39	34	30	27	24	22	20	19	17	16	15	14	14	13	12	12			
48	+	96	69	54	44	38	33	29	26	23	21	20	18	17	16	15	14	13	13	12	11	11		
49	+	86	64	51	42	36	31	28	25	23	21	19	18	17	16	15	14	13	12	12	11	11	10	
50	113	78	60	48	40	35	30	27	24	22	20	19	17	16	15	14	14	13	12	12	11	11	10	-
51	100	72	56	45	38	33	29	26	24	22	20	18	17	16	15	14	13	13	12	11	11	11	10	-
52	90	66	52	43	37	32	28	25	23	21	19	18	17	16	15	14	13	12	12	11	11	10	10	-
53	81	61	49	41	35	31	27	25	22	21	19	18	16	15	14	14	13	12	12	11	11	10	-	-
54	74	57	46	39	34	30	27	24	22	20	19	17	16	15	14	13	13	12	12	11	11	10	-	-
55	68	53	44	37	32	29	26	23	21	20	18	17	16	15	14	13	13	12	11	11	10	10	-	-
56	63	50	42	36	31	28	25	23	21	19	18	17	16	15	14	13	12	12	11	11	10	-	-	-
57		47	40	34	30	27	24	22	20	19	17	16	15	14	14	13	12	12	11	11	10	-	-	-
58			38	33	29	26	24	21	20	18	17	16	15	14	13	13	12	11	11	10	10	-	-	-
59			36	32	28	25	23	21	19	18	17	16	15	14	13	12	12	11	11	10	10	-	-	-
60				31	27	25	22	20	19	18	16	15	14	14	13	12	12	11	11	10	-	-	-	-
61				30	26	24	22	20	18	17	16	15	14	13	13	12	12	11	11	10	-	-	-	-
62					26	23	21	20	18	17	16	15	14	13	13	12	11	11	10	10	-	-	-	-
63					25	23	21	19	18	17	15	15	14	13	12	12	11	11	10	-	-	-	-	-
64						22	20	19	17	16	15	14	14	13	12	12	11	11	10	-	-	-	-	-
65						21	20	18	17	16	15	14	13	13	12	11	11	10	10	-	-	-	-	-
66							19	18	17	16	15	14	13	12	12	11	11	10	10	-	-	-	-	-
67							19	17	16	15	14	14	13	12	12	11	11	10	-	-	-	-	-	-
68								17	16	15	14	13	13	12	12	11	11	10	-	-	-	-	-	-
69									16	15	14	13	13	12	11	11	10	10	-	-	-	-	-	-
70									15	15	14	13	[illegible]	12	11	11	10	-	-	-	-	-	-	-
71										14	13	13	12	12	11	11	10	-	-	-	-	-	-	-
72										14	13	13	12	11	11	10	10	-	-	-	-	-	-	-
73											13	12	12	11	11	10	10	-	-	-	-	-	-	-
74											13	12	[illegible]	11	11	10	-	-	-	-	-	-	-	-
75												12	11	11	11	10	-	-	-	-	-	-	-	-
76												12	11	11	10	10	-	-	-	-	-	-	-	-
77													11	[illegible]	10	-	-	-	-	-	-	-	-	-
78													11	11	10	-	-	-	-	-	-	-	-	-
79														10	10	-	-	-	-	-	-	-	-	-
80														10	-	-	-	-	-	-	-	-	-	-
81															-	-	-	-	-	-	-	-	-	-
82																-	-	-	-	-	-	-	-	-
83																-	-	-	-	-	-	-	-	-
84																	-	-	-	-	-	-	-	-
85																	-	-	-	-	-	-	-	-

LESS THAN 10% RELATIVE HUMIDITY

+ Safe exposure for 120+ minutes and longer towards top-left of the Table.

- Safe exposure for less than 10 minutes and shorter towards bottom-right of the Table.

Table F: 99% safe exposure times (in minutes) for unacclimatised fit, young exposees clothed in overalls and working at 310J/sec in air movements of 0.76 or 1.02 m/sec.

DRY BULB °C \ WET BULB °C	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
32	+	+	+	+	+	107																		
33	+	+	+	+	+	93	64																	
34	+	+	+	+	+	82	59	45																
35	+	+	+	+	115	74	54	43	35															
36	+	+	+	+	99	67	50	40	33	29														
37	+	+	+	+	87	61	47	38	32	27	24													
38	+	+	+	+	77	56	44	36	30	26	23	21												
39	+	+	+	105	69	52	41	34	29	25	23	20	18											
40	+	+	+	91	63	48	39	33	28	24	22	20	18	16										
41	+	+	+	81	58	45	37	31	27	24	21	19	17	16	15									
42	+	+	112	72	53	42	35	30	26	23	20	19	17	16	14	13								
43	+	+	96	66	50	40	33	28	25	22	20	18	16	15	14	13	12							
44	+	+	85	60	46	38	32	27	24	21	19	18	16	15	14	13	12	11						
45	+	119	76	55	43	36	30	26	23	21	19	17	16	15	14	13	12	11	11					
46	+	102	68	51	41	34	29	25	22	20	18	17	15	14	13	12	12	11	10	10				
47	+	89	62	47	38	32	28	24	22	20	18	16	15	14	13	12	11	11	10	10	-			
48	+	79	57	44	36	31	27	24	21	19	17	16	15	14	13	12	11	11	10	10	-	-		
49	107	71	53	42	35	29	26	23	20	18	17	16	14	13	12	12	11	10	10	-	-	-	-	
50	93	64	49	39	33	28	25	22	20	18	16	15	14	13	12	12	11	10	10	-	-	-	-	-
51	82	59	46	37	31	27	24	21	19	17	16	15	14	13	12	11	11	10	10	-	-	-	-	-
52	73	54	43	35	30	26	23	21	19	17	16	14	13	13	12	11	10	10	-	-	-	-	-	-
53	66	50	40	34	29	25	22	20	18	17	15	14	13	12	12	11	10	10	-	-	-	-	-	-
54	61	47	38	32	28	24	22	19	18	16	15	14	13	12	11	11	10	10	-	-	-	-	-	-
55	56	44	36	31	26	23	21	19	17	16	15	14	13	12	11	11	10	-	-	-	-	-	-	-
56	52	41	34	29	25	23	20	18	17	15	14	13	12	12	11	10	10	-	-	-	-	-	-	-
57		39	33	28	25	22	20	18	16	15	14	13	12	11	11	10	10	-	-	-	-	-	-	-
58			31	27	24	21	19	17	16	15	14	13	12	11	11	10	10	-	-	-	-	-	-	-
59			30	26	23	20	19	17	16	14	13	13	12	11	10	10	-	-	-	-	-	-	-	-
60				25	22	20	18	17	15	14	13	12	12	11	10	10	-	-	-	-	-	-	-	-
61				24	21	19	18	16	15	14	13	12	11	11	10	10	-	-	-	-	-	-	-	-
62					21	19	17	16	15	14	13	12	11	11	10	-	-	-	-	-	-	-	-	-
63					20	18	17	15	14	13	12	12	11	10	10	-	-	-	-	-	-	-	-	-
64						18	16	15	14	13	12	11	11	10	10	-	-	-	-	-	-	-	-	-
65						17	16	15	14	13	12	11	11	10	10	-	-	-	-	-	-	-	-	-
66							16	14	13	12	12	11	10	10	-	-	-	-	-	-	-	-	-	-
67							15	14	13	12	12	11	10	10	-	-	-	-	-	-	-	-	-	-
68								14	13	12	11	11	10	10	-	-	-	-	-	-	-	-	-	-
69									13	12	11	11	10	-	-	-	-	-	-	-	-	-	-	-
70									12	12	11	10	10	-	-	-	-	-	-	-	-	-	-	-
71										11	11	10	10	-	-	-	-	-	-	-	-	-	-	-
72										11	11	10	10	-	-	-	-	-	-	-	-	-	-	-
73											10	10	-	-	-	-	-	-	-	-	-	-	-	-
74											10	10	-	-	-	-	-	-	-	-	-	-	-	-
75												10	-	-	-	-	-	-	-	-	-	-	-	-
76												-	-	-	-	-	-	-	-	-	-	-	-	-
77													-	-	-	-	-	-	-	-	-	-	-	-
78													-	-	-	-	-	-	-	-	-	-	-	-
79														-	-	-	-	-	-	-	-	-	-	-
80														-	-	-	-	-	-	-	-	-	-	-
81															-	-	-	-	-	-	-	-	-	-
82																-	-	-	-	-	-	-	-	-
83																-	-	-	-	-	-	-	-	-
84																	-	-	-	-	-	-	-	-
85																	-	-	-	-	-	-	-	-

LESS THAN 10% RELATIVE HUMIDITY

\+ Safe exposure for 120+ minutes and longer towards top-left of the Table.

\- Safe exposure for less than 10 minutes and shorter towards bottom-right of the Table.