THE INFLUENCE OF THE HUMIDITY OF THE AIR ON CAPACITY FOR WORK AT HIGH TEMPERATURES.

By H. M. VERNON, M.D. and C. G. WARNER, B.Sc.

(With Plate IV and 15 Figures in the Text.)

CONTENTS.

I. The importance of the humidity factor in work carried on at high temperatures.

Any European who has lived in the vegetation belts of the tropics can testify to the difference between the hot and dry seasons and the rainy seasons, as they affect working capacity. But the effects of somewhat similar atmospheric conditions may also arise in temperate climates in various industrial occupations. The influence of high temperature and humidity is a matter of increasing practical importance in this country, especially in relation to deep mining, where, owing to the gradual exhaustion of the shallower seams, coal and certain ores are being extracted at greater and greater depths. For instance, at Pendleton Colliery, in Lancashire, the dry-bulb temperature of the air is about 100° F. (37·8° C.), and the wet-bulb 85° F. (29·4° C.). In the Levant tin mine, Cornwall, Haldane (1905) found that the temperature of the workings varied from 80 to 93° F. (26·7–33·9° C.), the air being nearly saturated with moisture.

In addition to miners, many other industrial workers, such as those employed at steel furnaces, at the rolling mills of tinplate works, and in drawing the ovens used for firing pottery, are subjected to very high temperatures for intermittent periods, whilst the men working in the stokeholds and engine rooms of steamers may be exposed to such temperatures throughout their working shift. Hence the question of artificially improving the atmospheric conditions constantly arises.

An extreme instance of high temperature and humidity is met with at the Morro Velho gold mine in Brazil. Davies (1921) found that the dry-bulb temperature in the deepest workings, some 6000 ft. below the surface, averaged 101·5° F. (38·6° C.), and the wet-bulb 87° F. (30·6° C.), the limit of human endurance being almost reached, even for natives accustomed to high temperatures. In 1922 a powerful refrigerating plant was installed at the surface, which cooled the intake air to 43° F. (6·1° C.), and in consequence the dry-bulb temperature of the air in the workings fell to 97·4° F. (36·3° C.), and the wet bulb to 80° F. (26·7° C.). The comfort and efficiency of the miners were so much improved that in the 16 months subsequent to the introduction of the cooling plant the output from the mine increased 12 per cent., whilst the number of fatal accidents fell to 6, as compared with the 20 incurred in the preceding 16 months. Unfortunately cooling plants are too expensive for most purposes. Other and simpler methods have been suggested, but it is difficult to decide on their merits, as we are troubled with a fundamental conflict of opinion.

II. THE PRESENT POSITION OF PHYSIOLOGICAL THEORY AND KNOWLEDGE.

The wet-bulb hypothesis. As the result of numerous experiments on himself and other subjects, Haldane (1904 *et seq.*) came to the conclusion that the maximum temperature which can be borne for some hours without the development of pathological symptoms such as heat stroke, depends on the wet-bulb temperature alone, the dry-bulb being of no significance. Haldane has since stated (1929), with reference to coal miners, that "for physiological purposes it is the wet-bulb temperature that we want." He lays so much stress on keeping down the humidity of the air that when discussing the atmospheric conditions in the Rand mines (1929), where the air is kept almost saturated with moisture in order to reduce dust inhalation, he suggested that the dust should be laid by other means not involving the addition of moisture. He claims that the wet-bulb temperature would be reduced, and that the air would reach the working places with its power to cool through evaporation of sweat almost unimpaired.

Effective temperature. On the other hand, Yaglou, Houghton and McConnell (cf. Yaglou, 1926, 1927) maintain that even at high atmospheric temperatures the dry-bulb temperature exerts a considerable influence as well as the wet-bulb. At the research laboratories, Pittsburg, are installed two experimental chambers side by side, in both of which the temperature and humidity of the air can be varied between wide limits. In their experiments the subjects passed backwards and forwards from one chamber to the other, and various combinations of wet- and dry-bulb temperatures were arranged so as to induce the same sensations of warmth. In one of the chambers the velocity of the air could be raised to 700 ft. per min., and the three factors of dry-bulb temperature, wet-bulb temperature and air velocity were combined into a single measure termed *effective temperature.* Charts have been constructed from which it is possible to ascertain the effective temperature corresponding to any combination of the three factors, as they affect men normally clothed, and men stripped to the waist.

The scale is based on the Fahrenheit scale, and consequently we have recorded the temperature data in this paper on the same scale, but we have quoted some of them on the Centigrade scale in addition. We see from the sample data recorded—which apply to resting men stripped to the waist—that still air with both wet- and dry-bulb temperatures at 70° F. would have an effective temperature of 70°, but if the wet-bulb were 70° and the dry-bulb 100°, the effective temperature would be 80·5°, or 10·5° higher. At higher temperatures the influence of the dry-bulb temperature is less important, but we see that even with a wet-bulb of 90° a dry-bulb of 120° is said to raise the effective temperature 5·5°.

Dry-bulb temperature		Wet-bulb temperature		Effective temperature		Rise in effective temperature due to dry-bulb	
° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.
70	21·1	70	21·1	70	21·1		
100	37·8	70	21·1	80·5	26·9	10·5	5·8
80	26·7	80	26·7	80	26·7		
110	43·3	80	26·7	88·1	31·2	8·1	4·5
90	32·2	90	32·2	90	32·2		
120	48·9	90	32·2	95·5	35·3	5·5	3·1

Arguing from these and other data, Yaglou suggests that the air in hot mines ought to be conditioned by *increasing* its humidity. An addition of moisture to the air by spraying or other means would have no effect whatever on the wet-bulb temperature, but it would lower the dry-bulb, and if sufficiently thorough it would saturate the air with moisture and lower the dry-bulb to the same figure as the wet-bulb. The effective temperature would thereby be lowered (*e.g.* by 5·5° to 10·5° in the above-mentioned instances) and the men would be able to work better. Yaglou and his colleagues have made series of observations in which they performed mechanical work up to 210,000 ft. lb. (29,000 kg. m.) per hour at wet-bulb temperatures of 74° F. (23·3° C.) and upwards, and they claim that the increases in rectal temperature and pulse rate observed support the validity of the effective temperature scale as an index of working capacity, rather than that of the wet-bulb temperature.

The apparent contradiction between the views of Haldane and Yaglou may be dependent to a large extent on the fact that Haldane's wet-bulb hypothesis holds *only* when the entire surface of a man's body is covered with a film of evaporating moisture, and is ventilated by a fairly rapid air current. If the body is dry, or not thoroughly wetted, the dry-bulb temperature of the air must exert an influence. It also exerts an influence in still or slowly moving air, as is proved by observations on ventilated and unventilated wet-bulb thermometers. The question of the dryness or wetness of the body surface as a whole under various atmospheric conditions is not one about which accurate prediction can be made, as a rule, so it appeared to us to be desirable that further experimental evidence should be obtained concerning the effects of various atmospheric conditions on the physiological reactions of men engaged in heavy work, with a view to indicating those conditions which throw the least strain upon the body. We thought that the heavy work in question should be somewhat similar to that performed in many industrial occupations, rather than of an exceptional character. We accordingly selected step climbing in preference to work on a bicycle ergometer, which has been used by several previous investigators, or to the intermittent raising and lowering of a heavy weight (*e.g.* 40 lb.) by pulling with the arms on a handle and rope running over a pulley, as in the experiments of Houghten, Teague and Miller (1926). Furthermore, in order that we might get fairly steady reactions comparable to those of industrial workers who usually work for 3 or 4 hours at a stretch, we adopted a work period of 3 hours.

III. METHOD OF EXPERIMENT.

(1) *Description of the air-conditioning room.*

The observations to be described were made on ourselves in the air-conditioning room (see Plate IV) at the London School of Hygiene and Tropical Medicine. This room is 21½ × 19 ft. in area, and 10 ft. in height. Its walls and ceiling are lined with a 2-in. layer of cork, set in bitumen, and this is covered with several layers of cement, paint and enamel. Heat conduction is thereby greatly reduced, but the concrete floor of the room conducts a good deal. The room is lit by two doubly glazed windows, each 6½ × 5 ft. in area, as well as artificially. It is connected with a Carrier air-conditioning plant located outside, which is able to give any dry-bulb temperature from 40 to 150° F., and air of any humidity up to saturated air at 100°. The air is driven by a centrifugal fan across the room through twenty air ducts (each 4 × 1½ in. in area), which are fixed at a height of 8 ft. 8 in. above floor level on the wall opposite the windows. Four of these ducts are shown in Plate IV. The air passes out of the room through a duct 30 × 21 in. in area, which is fixed at the lower corner of one of the windows. Most of this air recirculates through the circuit of water sprays and heating coils, and is driven back into the air-conditioning room, but there are two connections with the outside air, through one of which fresh air can be filtered and sucked in, and through the other of which (a short duct 7 in. square) it can be either discharged or sucked in.

The wet-bulb temperature of the air is set by means of a thermostat outside the room, and the dry-bulb, by one inside. Once equilibrium is attained, the air temperature remains remarkably steady, except that its dry-bulb temperature oscillates about 2° F. at 2-min. intervals, because of the alternate opening and closing of the steam valves.

(2) *Experimental routine of observations.*

In our observations, the steam heating and the fan were turned on at 8.30 a.m., and we started our 3-hour experiments at about noon. One subject (W.) ascended and descended two steps fifteen times a minute, synchronous with the ticks of a metronome. The height of the steps was 30·6 cm., or approximately 1 ft. The mechanical work done was thought to be more or less equivalent to that performed by an average coal miner, and it was for this reason that step climbing was the task chosen. Very little information is available, but Moss (1923) made observations on a single miner for three working shifts, and he found that—excluding an interval for a meal—he expired 28·4 litres per min. When doing work on a Martin's bicycle ergometer at the rate of 17,950 kg. m. per hour the miner expired 25·3 litres per min., and consumed 1138 c.c. of oxygen. Subject W. did 14,400 kg. m. of work per hour in step climbing and expired 21·3 litres per min., whilst he consumed 1040 c.c. of oxygen. However, he weighed only 137 lb., as compared with the 148 lb. of the miner, who was well known to be an exceptionally good worker.

Subject W. step climbed for a period of 25 min., during the last 10 of which he breathed into a Douglas bag, which was slung from a wooden framework. He then rested for 5 min., during which time the rectal temperature was taken, and a measured quantity of water was drunk. The water contained 0·18 per cent. of NaCl and 0·02 per cent. of KCl, in correspondence with the composition of the sweat. During the first 15 min. of each 25-min. spell the atmospheric conditions to which the body surface of subject W. was exposed were ascertained by getting him to carry in turn a hygrometer, a dry kata-thermometer and a wet kata-thermometer. The instruments were held at a distance of about a foot from the body by means of a clamp, and they accordingly underwent the additional air movement induced by the subject's moving up and down the steps, as well as that due to the artificial ventilation. Corresponding observations were made with these instruments when stationary, and we found that, in winter, the stationary dry kata indicated a mean air velocity of only 46 ft. per min., as compared with one of 93 ft. in the carried instrument, whilst in summer the velocities observed were 49 and 86 ft. respectively. The air current through the room was not intentionally changed in any of the experiments, but it is possible that the centrifugal fan did not always run at exactly the same rate.

The hygrometer was read when fixed to the thermometer stand, 4 ft. above floor level, as well as after being carried by the subject. It was vigorously fanned for a minute before reading, but in moist air its wet-bulb temperature was only 0·1° F. lower than the carried thermometer, and in dry air 0·2° lower. The readings of the carried thermometer were used for calculating the humidity of the air, as it was thought that they gave a slightly more accurate measure of the humidity of the air in contact with the skin of the step-climbing subject than the ventilated thermometer readings would have done. The humidities quoted in Tables I and II (see p. 438–9) were calculated from Jones' tables (1924).

(3) *Correction of observations for radiation effects.*

Though the air-conditioning room was heated up for 3½ hours before each experiment, its walls and floor never quite attained the air temperature registered by the hygrometer. This was ascertained by an instrument invented by one of us, called the *globe thermometer*, which is shown in Plate IV. It consists of a 6-in. copper globe, painted matt black, with an ordinary thermometer fixed by the cork in the tubulure so as to have its bulb in the centre of the globe. The instrument has been employed (Vernon, 1930, 1932) to summate the radiation received from all sources in a room, both positive and negative, for it was shown that its readings indicate the combination of air temperature and of radiation as they affect the human subject. It was found that, on an average, the globe thermometer temperature was 0·7° F. lower than the hygrometer (dry bulb) reading when the room was at 80–90°, and 1·5° lower when it was at 90–100°. The reduction varied considerably in different experiments, and in two instances it amounted to 2·3°. As this globe thermometer temperature appeared to us to be a more accurate index of the temperature conditions affecting the subjects than the hygrometer temperature, its readings were taken as the correct dry-bulb temperature, and they are quoted in Tables I and II as "air temperature corrected for radiation." The uncorrected readings are also recorded, and the differences between the two indicate the radiation effect. As regards the wet-bulb temperature, it is known that if the dry-bulb temperature is raised or lowered x degrees, the wet bulb is automatically raised or lowered approximately four-tenths of x degrees. Numbers of observations were made in still air and in moving air (270 ft. per min.) with a hygrometer which was alternately exposed to and protected from the radiation of a gas fire, and they showed that the radiation raised the dry- and wet-bulb temperatures approximately in the proportions mentioned. Hence the wet-bulb temperatures recorded in Tables I and II have been corrected correspondingly, but the uncorrected values are quoted in addition.

(4) *Clothing.*

In order to avoid the variable factor induced by the wearing of clothes, which would be dry at the start and damp later on, subject W. did not wear any clothes at all, save shoes, in any experiment. Subject V. likewise wore no clothes except in the two experiments made in moist air at 70°, when he wore flannel trousers, as he felt chilly.

IV. THE PHYSIOLOGICAL REACTIONS STUDIED IN RELATION TO TEMPERATURE AND HUMIDITY.

(1) *The pulse rate.*

The pulse rate is the most readily ascertainable of all the physiological reactions of the body, and we found that it was very sensitive to differences of air temperature and humidity. As is well known, the heart beat is greatly influenced by physical fitness, and in order that subject W. might be well adapted to the 3-hour spells of step climbing, he made two preliminary 3-hour experiments at a temperature of about 72° F. (d. b.), on November 25 and 27, one experiment at 79° on December 2, and one at 84° on December 4. The experiments made on subsequent days from December 8 onwards till March 12 are recorded in Table I, except for those on December 30, January 1 and 3, when the subject did 3-hour spells of step climbing at a temperature of about 64° in order to keep himself fit. From January 5 onwards the experiments were—with one exception—made regularly on the Monday, Wednesday and Friday of each week, and a similar procedure was adopted in most of the summer experiments, which lasted from July 10 to August 20 (cf. Table II). In the summer, the subject made no preliminary experiments in order to get into training, so the data obtained in the first of the recorded experiments (No. 33) are ignored in the subsequent averages of results.

In the winter two or more experiments were made at a wet-bulb temperature of approximately 70, 75 and 80° F., with the air 40, 60 and 95 per cent. saturated, and two were made in nearly saturated air at 85°. In the summer the experiments at 70°, and those in air of 60 per cent. saturation, were omitted.

The question of acclimatisation had constantly to be borne in mind, and it is discussed in detail in the next section of the paper. For reasons there brought forward, it is considered that the four pulse rates recorded in brackets in Table I are considerably influenced by lack of acclimatisation, and should therefore be ignored.

Pulse rate in relation to humidity. The pulse rates recorded in Tables I and II are the averages of the observations made during each period of 3 (or $2\frac{1}{2}$) hours. In subject W. there was not much variation during the course of the observational period (see Fig. 1). This shows the means of the five to eight experiments made in moist air (96 per cent. saturated) and dry air (40 per cent. saturated), at a wet-bulb temperature of 80°. In dry air the mean pulse rate varied less than 3 beats in winter and less than 2 beats in summer, though the average summer rate was 9 beats less than the winter one. The corresponding observations in moist air show a similar steadiness in winter, though a greater falling off in summer. The pulse rates of subject V., who was doing only the very light work needed for taking temperatures, exchanging gas bags, etc., are shown in the lower half of Fig. 1. They are about 26 beats per minute less than

Table I. *Temperature and energy expenditure of subject W. in relation to air temperature (winter).*

			Observed air temperature			Air temperature corrected for radiation		Dry kata (carried)								Skin temperature											
Date of exp.	No. of exp.	Duration in hours	d. b. (° F.)	w. b. (° F.)	Relative humidity (%)	d. b. (° F.)	w. b. (° F.)	Cooling power	Air velocity (ft.)	Wet kata (carried)	Corrected effective temperature (°)		Rectal temperature (° F.)	Pulse rate	Respiration rate	Forehead (° F.)	Chest (° F.)	Side (° F.)	Thigh (° F.)	Oxygen absorbed per min. (c.c.)	CO_2 in expired air (%)	Respiratory quotient	Work per hour in kg. m.	Gross mechanical efficiency (%)	Water drunk per hour (oz.)	Loss of moisture per hour (oz.)	Fatigue induced
16. xii	3	3	70·8	70·0	96	69·9	69·6	6·7	85	17·6	64·8	64·9	100·3	106·5	14·5	89·9	87·2	89·3	89·5	1041	4·24	·855	14,520	13·4	6·5	7·3	2
24. ii	26	3	71·2	70·3	96	70·4	70·0	6·7	91	17·6	65·1		100·3	103·7	14·8	90·5	86·5	88·6	86·4	1045	4·28	·847	14,480	13·4	7·0	7·2	2
9. i	7	3	77·3	75·1	90	76·6	74·8	5·2	98	14·9	71·6	71·3	100·7	111·3	15·2	94·2	88·7	90·0	89·8	1027	4·18	·855	14,380	13·5	5·7	14·0	3
27. ii	27	3	75·9	75·0	96	75·3	74·8	5·3	85	14·5	71·0		100·5	102·8	14·4	92·0	88·3	90·5	89·5	1037	4·27	·847	14,490	13·5	7·7	9·2	3
18. xii	4	3	84·1	72·3	57	83·3	72·0	3·4	97	16·8	73·8	72·1	100·4	(108·0)	15·1	94·8	90·3	91·9	94·9	992	4·14	·866	14,470	14·0	6·3	14·3	3
2. iii	28	3	80·4	69·9	59	79·1	69·4	4·2	88	18·2	70·4		100·5	103·2	14·8	95·0	90·2	90·6	91·8	1036	4·41	·862	14,330	13·3	7·3	9·5	3
8. xii	1	3	92·6	69·6	30	90·8	68·9	—	—	19·3	75·6	75·1	100·8	(124·8)	15·3	98·1	89·3	91·4	95·2	1005	4·33	·864	14,250	13·6	0·0	15·2	4
4. iii	29	3	87·7	70·8	43	86·7	70·4	2·6	—	18·1	74·7		100·4	107·0	14·8	96·2	89·4	90·2	93·2	1031	4·37	·858	14,350	13·4	8·0	13·3	2·5
5. i	5	3	88·2	76·0	56	86·7	75·4	2·5	—	15·1	77·3	76·6	100·3	(122·0)	14·2	97·3	88·3	90·8	94·7	1033	4·27	·853	14,440	13·4	7·0	14·3	3
6. iii	30	3	85·8	74·9	60	85·0	74·6	3·0	91	15·7	76·0		100·6	106·0	14·9	95·2	90·3	89·4	92·6	1013	4·32	·852	14,380	13·7	8·3	14·2	3
10. xii	2	3	81·7	79·0	89	80·8	78·6	3·9	91	12·6	76·4	76·7	99·8	108·5	14·9	94·2	91·5	92·8	93·1	998	4·20	·859	14,580	14·0	8·0	10·8	3
21. i	12	3	81·1	80·5	98	80·2	80·0	4·4	100	12·2	76·7		100·6	107·0	15·0	92·6	90·4	92·4	91·4	1027	4·09	·854	14,350	13·4	6·7	12·7	3
30. i	16	3	81·7	80·0	93	80·9	79·7	3·9	105	11·6	76·6		100·9	110·0	14·8	95·5	91·9	92·7	92·5	1076	4·30	·859	14,470	12·9	7·8	11·3	3
16. ii	23	3	81·3	80·2	96	80·4	79·8	4·1	95	12·2	76·9		100·6	108·0	14·8	93·8	91·6	92·1	92·0	1026	4·29	·851	14,330	13·5	8·7	18·7	2·5
18. ii	24	3	80·5	80·1	98	80·1	79·9	4·2	87	11·8	76·8		100·8	108·3	14·8	93·1	91·5	92·7	91·0	1041	4·28	·850	14,420	13·3	8·5	13·7	3
20. ii	25	3	80·7	80·1	98	80·0	79·8	4·2	92	12·0	76·7		100·4	107·2	14·9	92·6	90·6	92·0	91·5	1042	4·30	·853	14,480	13·4	8·0	11·8	3·5
7. i	6	3	93·8	75·5	42	91·5	74·6	—	—	15·4	78·8	79·5	100·8	(124·7)	15·3	97·9	89·0	90·3	94·6	1049	4·24	·860	14,400	13·2	9·5	16·7	4
10. iii	31	3	94·0	75·0	40	93·7	74·9	—	—	15·2	80·2		100·8	112·2	14·8	96·1	88·5	87·9	92·6	1057	4·28	·855	14,260	13·0	7·8	16·2	3·5
12. i	8	3	90·0	79·7	64	89·1	79·3	—	—	12·6	80·6	81·1	100·4	112·8	14·8	98·3	90·4	91·2	94·2	1003	4·30	·855	14,520	14·0	8·7	14·0	4
16. i	10	3	91·3	80·5	62	90·0	80·0	—	—	12·0	81·3		100·5	112·5	14·7	98·5	90·0	91·9	95·5	1008	4·29	·861	14,340	13·7	9·0	15·3	4
28. i	15	3	91·6	80·2	61	90·7	79·8	—	—	12·5	81·5		100·7	110·7	14·8	97·1	89·4	89·8	93·3	1078	4·28	·856	14,420	12·9	8·2	17·3	3·5
2. ii	17	2½	86·8	85·5	95	85·8	85·1	2·7	92	8·8	83·2	82·7	100·8	119·4	15·1	97·2	95·0	96·6	94·0	1113	4·22	·850	14,400	12·5	11·2	16·3	5 +
12. iii	32	2½	85·1	85·0	100	85·0	85·0	3·2	105	9·0	82·2		100·6	115·2	15·0	95·8	94·6	95·2	94·4	1081	4·24	·853	14,350	12·8	9·2	18·0	5 +
14. i	9	2	99·8	81·0	44	97·7	80·2	—	—	12·0	84·2	84·2	100·6	118·5	15·0	96·8	89·5	90·8	94·2	1025	4·22	·858	14,370	13·4	11·4	20·0	4 +
19. i	11	2½	100·1	80·4	42	97·8	79·5	—	—	12·6	83·9		100·6	121·8	15·0	97·6	90·2	90·6	94·6	1027	4·32	·870	14,410	13·5	10·4	19·6	4 +
23. i	13	2½	100·4	80·2	41	99·0	79·6	—	—	12·8	84·2		100·7	118·2	15·3	96·9	89·7	89·6	94·4	1042	4·37	·853	14,350	13·3	11·9	17·6	4 +
26. i	14	3	101·4	79·6	38	99·9	79·0	—	—	13·6	84·1		100·9	115·8	15·0	96·7	89·0	88·7	93·7	1036	4·14	·850	14,240	13·3	11·5	19·5	5
6. ii	19	2½	100·6	79·8	40	99·4	79·3	—	—	13·1	84·2		100·8	121·2	15·0	96·2	88·1	88·3	94·1	1070	4·32	·852	14,380	12·9	11·0	17·8	4 +
9. ii	20	2½	100·6	80·1	40	99·7	79·7	—	—	12·9	84·5		101·1	120·0	14·9	94·6	87·8	88·1	92·0	1094	4·36	·856	14,380	12·6	12·3	20·6	4 +
11. ii	21	2½	101·2	80·1	39	99·4	79·4	—	—	13·3	84·2		100·8	117·4	15·0	96·6	89·4	89·7	94·8	1044	4·29	·850	14,390	13·3	11·3	20·2	4 +
13. ii	22	2½	100·5	80·2	41	99·3	79·7	—	—	12·9	84·3		100·7	117·2	15·1	96·4	89·5	89·8	93·6	1015	4·33	·859	14,370	13·6	11·2	21·2	4 +
4. ii	18	3¼	101·5	80·9	41	100·2	80·4	—	—	—	85·0		101·6	82·5	15·9	94·3	90·8	88·2	90·4	358	3·57	·960	Nil	—	0·0	8·2	2·5

Table II. *Temperature and energy expenditure of subject W. in relation to air temperature* (*summer*).

			Observed air temperature			Air temperature corrected for radiation		Dry kata (carried)								Skin temperature											
Date of exp.	No. of exp.	Duration in hours	d. b. (° F.)	w. b. (° F.)	Relative humidity (%)	d. b. (° F.)	w. b. (° F.)	Cooling power	Air velocity (ft.)	Wet kata (carried)	Corrected effective temperature (°)		Rectal temperature (° F.)	Pulse rate	Respiration rate	Forehead (° F.)	Chest (° F.)	Side (° F.)	Thigh (° F.)	Oxygen absorbed per min. (c.c.)	CO_2 in expired air (%)	Respiratory quotient	Work per hour in kg. m.	Gross mechanical efficiency (%)	Water drunk per hour (oz.)	Loss of moistu per hour (oz.)	Fatigue induced
19. viii	49	3	76·2	75·1	96	75·5	74·8	5·2	83	15·0	71·2	71·3	100·4	102·7	11·5	93·9	89·1	91·0	89·5	1015	4·26	·861	13,990	13·3	7·0	9·8	2·5
20. viii	50	3	75·9	75·0	96	75·6	74·9	5·3	83	14·8	71·3		100·5	101·8	11·5	93·3	88·6	89·9	89·7	1003	4·25	·848	13,910	13·4	8·0	10·2	2·5
10. vii	33	3	81·2	80·5	97	80·8	80·3	4·0	86	11·5	77·7		100·6	109·6	12·9	93·2	91·2	93·7	91·9	1072	4·39	·855	13,840	12·5	7·7	15·0	4
13. vii	34	3	80·6	80·1	98	80·1	79·9	4·0	81	12·1	77·2	77·2	100·3	106·7	12·2	93·8	91·0	92·5	91·9	1039	4·25	·819	13,890	12·9	7·3	11·2	4
15. vii	35	3	81·3	80·3	96	80·9	80·1	4·0	91	12·2	77·5		100·4	104·1	12·7	92·3	90·3	92·2	91·8	995	4·35	·845	13,800	13·4	8·5	12·3	3·5
17. vii	36	3	80·9	80·0	96	80·6	79·9	4·1	90	12·1	77·2		100·3	103·8	12·8	92·5	91·2	92·4	91·9	1037	4·19	·851	13,900	12·9	7·0	9·0	4
20. vii	37	3	80·7	80·0	97	80·2	79·8	4·2	91	11·7	77·0		100·5	110·5	11·8	92·5	90·3	91·5	90·8	1008	4·25	·849	13,800	13·2	8·0	9·5	2·5
22. vii	38	3	81·0	80·0	96	80·7	79·9	4·1	86	11·8	77·2		100·3	104·8	11·9	93·4	90·6	91·8	91·2	1042	4·26	·839	14,000	13·0	8·2	12·0	3
14. viii	47	3	93·3	75·0	42	92·2	74·6	—	—	15·7	79·2	79·5	100·3	102·5	11·8	97·0	88·1	90·4	94·8	1003	4·32	·824	13,890	13·4	10·0	15·7	4
16. viii	48	3	93·8	75·5	42	93·1	75·2	—	—	16·5	79·9		100·4	107·1	11·3	95·3	87·1	89·1	93·6	1019	4·28	·835	13,860	13·1	10·0	15·9	3·5
10. viii	45	2½	85·6	85·0	98	85·5	85·0	2·8	85	8·7	83·0	82·9	100·8	114·6	14·1	95·2	93·8	95·2	94·1	1045	4·20	·859	13,900	12·8	9·8	23·8	3·5 +
12. viii	46	2½	85·5	85·0	98	85·3	84·9	2·9	86	8·8	82·9		100·8	114·0	12·9	95·4	94·3	94·6	93·9	1034	4·20	·851	13,940	13·0	10·0	16·4	4 +
24. vii	39	2½	100·2	80·1	41	98·5	79·4	—	—	13·3	84·1	84·2	100·6	110·8	14·0	95·8	87·8	89·7	94·3	1045	4·28	·827	13,880	12·8	7·1	18·8	4 +
27. vii	40	2½	100·7	79·9	39	98·9	79·2	—	—	12·7	84·1		100·7	111·3	13·2	96·1	89·2	91·0	94·4	1058	4·34	·840	13,960	12·7	9·4	17·8	3·5 +
29. vii	41	2½	100·9	80·1	40	99·5	79·5	—	—	12·6	84·4		100·7	106·8	13·3	95·6	87·8	89·2	94·0	1033	4·22	·825	13,820	12·9	9·6	19·2	3·5 +
31. vii	42	2½	100·9	80·3	40	99·2	79·6	—	—	12·8	84·3		100·6	113·4	13·6	96·4	88·6	89·9	94·7	1060	4·26	·827	13,800	12·6	8·7	19·8	4 +
4. viii	43	2½	100·6	80·0	40	99·1	79·4	—	—	13·2	84·2		100·7	113·5	13·9	96·1	89·3	90·4	94·3	997	4·25	·861	13,850	13·4	9·8	20·6	3·5 +
6. viii	44	2½	101·1	80·2	40	99·5	79·6	—	—	12·9	84·2		100·6	110·1	12·8	95·8	89·3	90·9	94·8	1036	4·31	·842	13,920	13·0	9·4	23·2	3·5 +

in the corresponding observations on subject W. The means of the sets of observations are recorded in Table III, and it will be seen that in both subjects, during the winter months, the pulse rate was about 10 beats faster in dry air than in moist air of the same wet-bulb temperature; but in summer the pulse of subject W. was only 5 beats faster in dry air than in moist air. In order to test the consistency of the results obtained, we calculated the probable error of the difference between the means from the equation:

$$\text{probable error } M_1 - M_2 = 0{\cdot}6745 \sqrt{\frac{\sigma_1^2}{N_1} + \frac{\sigma_2^2}{N_2}}.$$

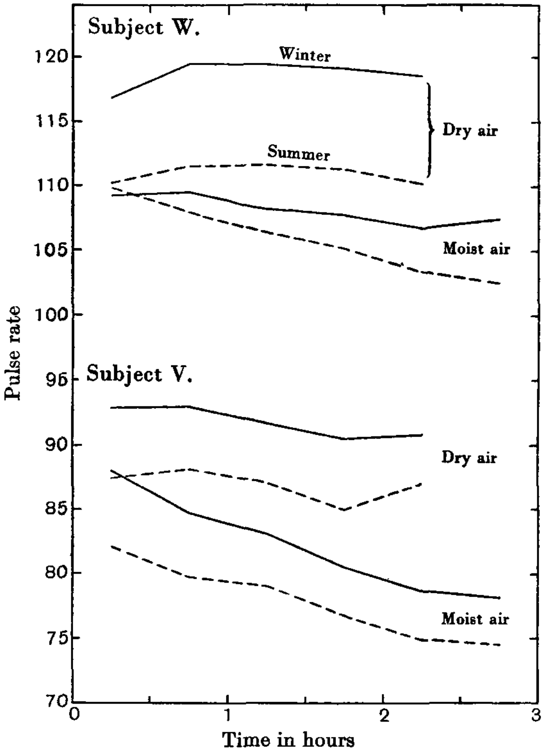

Fig. 1. Pulse rate in relation to humidity and season.

Table III. *Mean pulse rate in relation to humidity and season.*

Season	No. of exp.	Air temperature: Dry bulb ° F.	Air temperature: Wet bulb ° F.	Subject W. (heavy work): Moist air	Subject W. (heavy work): Dry air	Subject W. (heavy work): Excess in dry air	Subject V. (light work): Moist air	Subject V. (light work): Dry air	Subject V. (light work): Excess in dry air
Winter	6	80·4	79·6	108·2	118·8	10·6±·54	82·3	91·9	9·6±1·94
	8	99·0	79·6						
Summer	5	80·5	79·9	106·0	111·0	5·0±·97	77·9	86·9	9·0±1·19
	6	99·1	79·5						
Reduction of pulse in summer				2·2	7·8		4·4	5·0	

Though this equation underestimates the probable errors of small numbers of data such as were available in the present instance, they are sufficiently small to indicate that the differences of pulse rate observed are significant. That is to say, they indicate that the dry-bulb temperature had a considerable influence on the pulse rate, both in a heavy-working and a light-working subject.

Pulse rate in relation to wet- and dry-bulb temperatures. The effect of humidity was almost the same at all the temperatures investigated, as is shown in Fig. 2, where the pulse rate is plotted in relation to wet-bulb temperature. In this and subsequent figures the moist air observations are designated by a dot, and the dry air observations by a circle. The observations in air of 60 per cent. relative humidity are generally omitted as they were few in number, but Table I shows that they mostly fell between the values recorded at the two extreme humidities. Fig. 2 shows that there is no correspondence in the moist-air and dry-air pulse rates at any temperature in either subject. It can, in fact, be gathered from Fig. 3 that the pulse rates agree rather better with the dry-bulb temperature scale than with the wet-bulb.

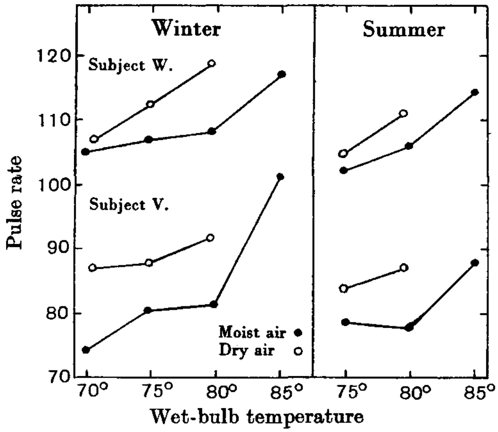

Fig. 2. Pulse rate in relation to wet-bulb temperature.

Pulse rate in relation to effective temperature. Fig. 4 shows that the pulse rate agrees much better with the effective temperature scale than with either of the other scales. The scale used is deduced from Yaglou's chart for resting men, stripped to the waist, at an air velocity of 90 ft. per min. If the results obtained in air of about 60 per cent. relative humidity are consulted, it will be found that they are in good agreement with the effective temperature curves drawn in Fig. 4, whereas they fall more or less between the moist air and dry air curves drawn in Fig. 2.

The winter observations on subject W. show a particularly close correspondence with the effective temperature scale, but the summer ones do not. It appears that during summer, owing to his being more acclimatised to high temperature than in winter, he was relatively less responsive to the dry-bulb temperature of the air, so the effective temperature scale made too great an allowance for this dry-bulb factor. It is true that the summer observations on subject V. show as good an agreement with the effective temperature scale as the winter observations, but his pulse rate was not so reliable as that of subject W., owing to the variable character of the light work on which he was engaged.

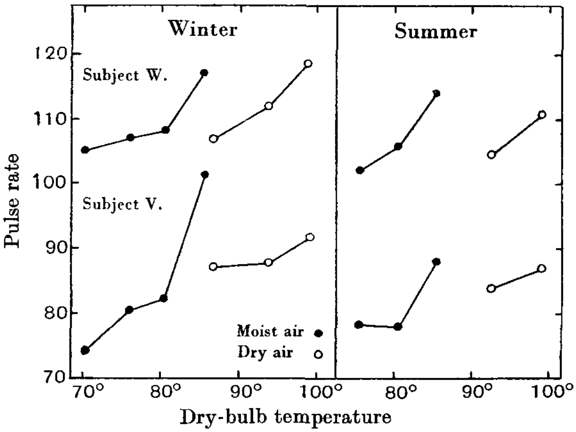

Fig. 3. Pulse rate in relation to dry-bulb temperature.

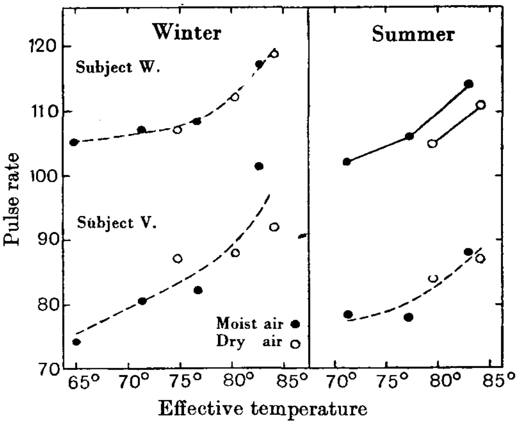

Fig. 4. Pulse rate in relation to effective temperature.

Pulse rate in relation to wet kata-thermometer cooling power. In Fig. 5 the pulse rates are plotted in relation to the wet kata cooling power (of the carried kata), and it will be seen that they show a similar relationship to that observed between pulse rate and wet-bulb temperature. This would naturally be expected, as the air velocity was practically the same throughout, and Hill, Vernon and Hargood-Ash (1922) showed that at ordinary humidities the cooling power of the wet kata is independent of the dry-bulb temperature. The relationship of the pulse rate to the dry kata cooling power would be similar to that between pulse rate and dry-bulb temperature; but owing to the high air temperature it was not possible to ascertain the dry kata cooling power in over half of the experiments.

Observations made by Campbell and Angus (1928) in dry air and moist air on three resting subjects showed that at dry-bulb temperatures of 68–95° the pulse rate was more closely correlated with effective temperature than with dry kata cooling power. No comparisons were made between pulse rate and wet kata cooling power or wet-bulb temperature.

It might be thought that the pulse rate would be related to absolute humidity, for the rate of evaporation of moisture from the body surface depends on the difference between the moisture content of the air and the moisture content of air saturated at the skin temperature. No relationship seemed to hold, however, for though the pulse rate was higher in dry air which caused rapid evaporation, than in moist air of the same wet-bulb temperature which caused slower evaporation, it was likewise quickened by raising the wet-bulb temperature, though in this case the rate of evaporation was diminished.

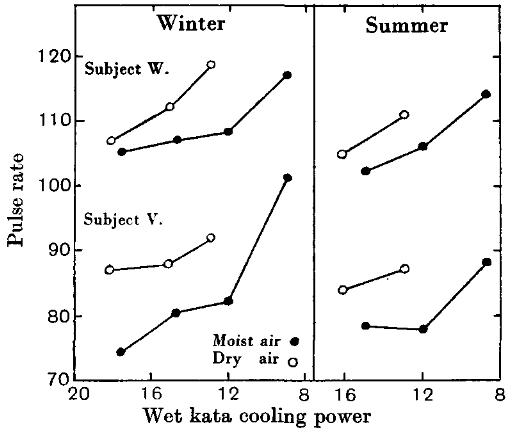

Fig. 5. Pulse rate in relation to wet kata cooling power

Pulse rate in relation to acclimatisation. It is probable that the human body shows some degree of acclimatisation in most of its physiological reactions at different seasons of the year. For instance, Vernon, Bedford and Warner (1926) showed that in summer the hundreds of British factory workers tested experienced a given sensation of warmth or coolness when the air of the factories was 5° F. (2·8° C.) warmer than in winter, and had a cooling power about 1 unit lower. Again, Yaglou and Drinker (1928) found that the hundreds of Americans tested by them at Harvard were comfortably warm at an effective air temperature of 70·5° in summer, and one of 66·0° in winter, or 4·5° less. In addition to seasonal acclimatisation, a smaller degree of acclimatisation is experienced from day to day, according to the vagaries of the weather, and to alterations of the indoor temperatures experienced.

It has already been stated that four of the pulse rates recorded in Table I were excluded because they were considerably influenced by lack of acclimatisation. They relate to experiments 1, 4, 5 and 6, whilst the pulse rates of the intermediate experiments, Nos. 2 and 3, were not considered to indicate lack of acclimatisation. The explanation of this arbitrary selection depends on the fact that acclimatisation is related chiefly to the *dry-bulb temperature*, which was a good deal higher in the excluded experiments than in the included ones. The relationship in question is indicated by the data in Table IV, which include the first two of the summer observations as well as the first six of the winter ones. It will be seen that the pulse rate of subject W. in the early experiments made at a dry-bulb temperature of 77·9° showed only a very slight excess over that observed in the later experiments when he was more acclimatised. Subject V. showed a lower pulse rate in the early experiments than in the later ones, so that on an average for the two subjects there was no appreciable difference of pulse rate. In the early experiments made at a dry-bulb temperature of 89·7°, however, the pulse rate of subject W. was 15·4 beats higher than in the later experiments, whilst in subject V. it was 13·9 beats higher. At the intermediate dry-bulb temperature of 83·3° the pulse rate showed an intermediate increase of about 5 beats. The wet-bulb temperature was lower in the high dry-bulb experiments than in the others, so it could not have been accountable for the acclimatisation. Further evidence bearing on the importance of the dry-bulb temperature is adduced in the section of this report describing skin temperatures.

Table IV. *Pulse rate indicating the dependence of acclimatisation on dry-bulb temperature.*

		Air temperature				Subject W.				Subject V.			
Date of unacclimatised exp.	No. of exp.	Dry bulb ° F.		Wet bulb ° F.		Pulse when unacclimatised	Pulse when acclimatised	Difference		Pulse when unacclimatised	Pulse when acclimatised	Difference	
16. xii	3	69·9	77·9	69·6	77·1	106·5	103·7	+ 2·8	+ 2·0	—	—	—	− 3·5
13. vii	34 (=2)	80·1		79·9		106·7	105·8	+ 0·9		72·5	79·3	− 6·8	
10. vii	33 (=1)	80·8		80·3		109·6	105·8	+ 3·8		79·0	79·3	− 0·3	
10. xii	2	80·8		78·6		108·5	108·1	+ 0·4		—	—	—	
18. xii	4	83·3		72·0		108·0	103·2		+ 4·8	92·4	86·5		+ 5·9
5. i	5	86·7	89·7	75·4	73·0	122·0	106·0	+16·0	+15·4	103·2	83·3	+19·9	+13·9
8. xii	1	90·8		68·9		124·8	107·0	+17·8		—	—	—	
7. i	6	91·5		74·6		124·7	112·2	+12·5		95·7	87·8	+ 7·9	

So marked is the acclimatisation effect in experiments made at high dry-bulb temperatures that it can be seen developing from day to day. In Fig. 6 are plotted the pulse rates observed in all the experiments made on subject W. at a wet-bulb temperature of 80°, including those in air 62 per cent. saturated, and it will be seen that the last four winter experiments made in dry air (40 per cent. saturated) were on consecutive occasions. The mean pulse rates were 121·2, 120·0, 117·4 and 117·2, so they fell steadily. The last three winter experiments made in moist air were likewise consecutive, but they show very little falling off, and in fact they indicate no lower rate than was observed in two of the three earlier experiments. In the summer a series of six consecutive experiments was first made in moist air at 80°, followed by a series of six consecutive experiments in dry air. The pulse rates observed were rather irregular, in spite of the great regularity observed by the subject in his habits of life, and they show very little sign of daily increase in acclimatisation. What they do show is the considerable reduction of the pulse rate in the dry-air experiments, on that observed in the winter, and the small reduction in the moist-air experiments.

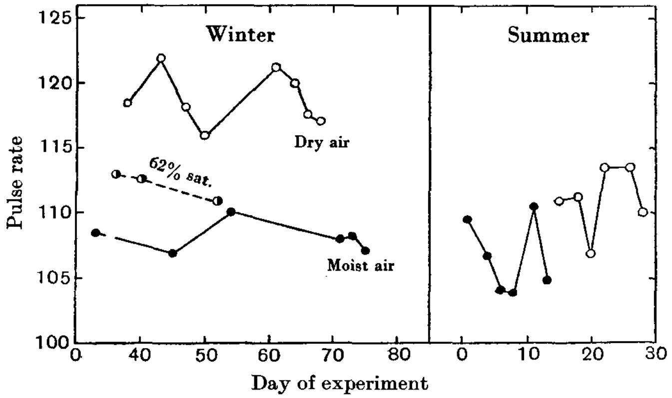

Fig. 6. Pulse rates observed in dry and moist air at a wet-bulb temperature of 80° F.

As already mentioned, these reductions were due to the acclimatisation of the subject to the summer weather, for meteorological records indicated that the average outside temperature during the period of the summer experiments was about 22° higher than during the winter ones. It was calculated that, making due allowance for sleeping in an unheated room by night and dwelling in a heated one by day, the skin surface of the subject's face was exposed to a mean temperature of about 64° in summer and 54° in winter. It follows that in the dry-air experiments he was subjected to a rise of only 35° in summer as compared with one of 45° in winter.

As we spent only 9 or 10 hours per week in the hot room, it seems likely that the extent of our acclimatisation was by no means so great as that which would be experienced by a coal miner who worked 45 hours per week underground in a hot place. Under such conditions there can be little doubt that the pulse rate observed in dry air, as compared with that in moist air, would show less than the 5 beats excess observed in the present experiments.

In the winter experiments, subject V. showed less acclimatisation than subject W. to dry air, but in the summer experiments he showed much more, his pulse rate falling gradually from 90·6 to 82·3.

(2) *Respiration rate.*

The respiration rate of subjects W. and V. was taken regularly every half hour in all the experiments, and it is recorded for subject W. in Tables I and II. In the winter it was scarcely influenced at all by atmospheric conditions. For instance, in the sets of observations made at a wet-bulb temperature of 80°, it averaged, in subject W., 14·9 per min. when the air was moist and 15·0 when it was dry, whilst in subject V. the rates were 14·5 and 14·3 respectively. In the summer observations, however, the rate of subject W. was 12·3 in moist air and 13·5 in dry air; *i.e.* the respiration was distinctly slower than in winter. Subject V. showed very little change, his rate being 14·1 and 14·2 respectively.

(3) *Body temperature.*

It will be shown later on that dry air induced considerably more fatigue than moist air of the same wet-bulb temperature, and we have just seen that it caused a substantial increase of pulse rate. It might therefore be expected to have some influence on the body temperature, and we tested this surmise by taking our rectal temperatures regularly during the 5-min. rest pauses. The mean values observed by subject W. are recorded in Tables I and II, whilst the average values for both subjects are plotted in Fig. 7 in relation to wet-bulb temperature. It will be seen that the body temperature rose as the air temperature rose, but that it was always distinctly higher in dry air than in moist air. The means of the sets of observations made at a wet-bulb temperature of 80° F. are recorded in Table V, and it will be seen that the body of subject W. was about 0·3° F. warmer in dry air than in moist air, whilst that of subject V. was 0·6° warmer. These differences are probably statistically significant with one exception, and they persisted throughout the $2\frac{1}{2}$ or 3 hours for which the experiments lasted. The body temperature rose about 0·2° between the first and second half hours, and then fell slowly.

Table V. *Mean rectal temperature in relation to humidity and season.*

		Air temperature		Subject W.				Subject V.			
Season	No. of exps.	Dry bulb ° F.	Wet bulb ° F.	Moist air ° F.	Dry air ° F.	Excess in dry air ° F.		Moist air ° F.	Dry air ° F.	Excess in dry air ° F.	
Winter	6 8	80·4 99·0	79·6 79·6	100·52	100·78	·26 ± ·105	·28 ± ·062	99·96	100·51	·55 ± ·098	·64 ± ·069
Summer	5 6	80·5 99·1	79·9 79·5	100·36	100·65	·29 ± ·028		99·76	100·48	·72 ± ·082	
Reduction of rectal temperature in summer	...	...	...	0·16	0·13			0·20	0·03		

The relationship of body temperature to the effective temperature scale is shown in Fig. 8. The agreement was fairly good in the winter observations, especially for subject W., but not at all good in the summer, so these body-temperature results correspond fairly well with the winter and summer pulse rates.

(4) *Skin temperature.*

It is a matter of common experience that the skin of the face feels warmer at high atmospheric temperatures than at low ones, but it is difficult to estimate what is happening when the skin is damp from perspiration, for the cooling effect of the evaporating moisture may, or may not, counteract the tendency of the skin temperature to rise. In order to determine accurately the changes in our skin temperature in the air-conditioning room, we measured it systematically during the last 10 min. of each half-hour spell.

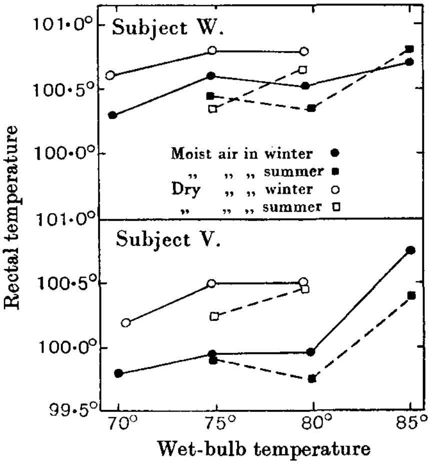

Fig. 7. Body temperature in relation to wet-bulb temperature of air.

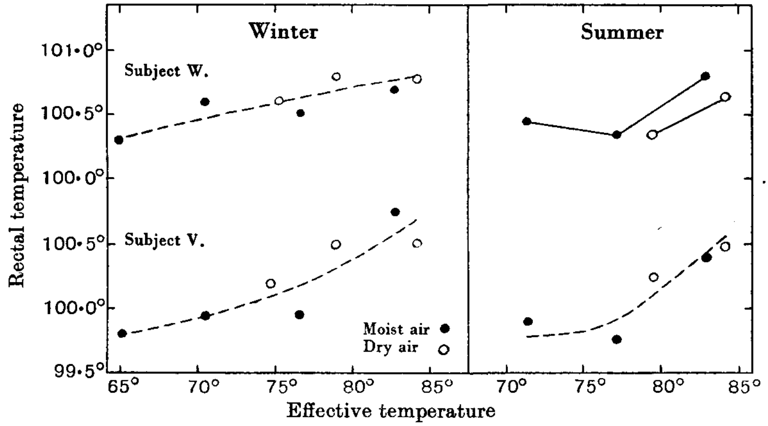

Fig. 8. Body temperature in relation to effective temperature of air.

Experimental procedure. We made our measurements by means of a Moll thermopile, the instrument being held within a quarter of an inch of the forehead, the chest (between the nipples), the right side (just above the crest of the ilium), and in the middle of the thigh, in front. The thermopile has to be held in position only for 5 sec., and the deflection of the galvanometer connected with it enables one to determine the skin temperature (cf. Vernon, 1928). Subject W. held the thermopile in position whilst step climbing, except in the thigh observations.

In order to determine how far the results obtained agreed with those yielded by other methods, subject V. made control observations with a delicate skin thermometer in the last eleven of the summer experiments (Nos. 40–50). The thermometer bulb was rolled over the skin for $1\frac{1}{2}$ min., and according to Campbell and Angus (1928) this method gives almost the same results as are yielded by a thermoelectric junction (cf. Benedict, 1925). The results obtained showed that in moist air the two methods gave exactly the same mean temperature, though there were small differences in different localities. In dry air, however, the surface thermometer gave a mean excess of 1·3° over the thermopile observations. This may have been due partly to the direct influence of the air temperature on the thermometer, as it was higher than that of the skin, but in some localities (chest, thigh) the thermometer registered 2·5°–2·7° above that indicated by the thermopile. This difference suggests that there was some other explanation; *e.g.* the rapidly evaporating layer of sweat on the skin may have cooled the bulb of the thermometer—which was pressed firmly on the skin—to a less extent than its radiation cooled the thermopile.

When comparing the thermopile and the thermometer, observations were made on the cheek as well as on the forehead. The temperatures showed close agreement, so it is probable that they apply to the skin of the face taken as a whole. The temperatures of the chest and side also corresponded fairly well, so they are averaged in Fig. 9 and Table VI under the designation "trunk temperature"; but it is not implied that they yield a fair measure of the whole trunk surface.

Temperatures observed. The skin temperatures observed in subject W. in each experiment are recorded in Tables I and II. The mean values are plotted in Fig. 9, and it will be seen that when the face temperature was plotted in relation to the wet-bulb scale there was no correspondence between the dry air and the moist air results. When plotted according to the dry-bulb scale there was a very good agreement, both in summer and winter, whilst there was a moderately good agreement when they were plotted on the effective temperature scale. The trunk temperatures gave a very different result. When plotted on the wet-bulb scale the moist air and dry air results showed a certain amount of correspondence, but when plotted on the dry-bulb scale the trunk temperature was found to rise rapidly with rise of moist-air temperature, and to fall in the dry air observations, with complete break of continuity. This differentiation of moist air and dry air reactions is likewise shown when the results were plotted on the effective temperature scale.

The skin temperatures of subject V., when plotted on the three scales, showed roughly corresponding differences to those shown by subject W., though they were not so marked. The correspondence between the two subjects is brought out by the mean results recorded in Table VI, which relate to the sets of experiments made at a wet-bulb temperature of 80°. They show that in moist air the face temperature of both subjects was 0·4–1·8° warmer than that of the trunk. In dry air, however, it was 6·9° warmer in subject W., and 4·6° warmer in subject V. The hot dry air raised the face temperature 1·8–3·0° above that observed in moist air, and this provoked such a considerable evaporation of sweat from the skin of the trunk as to cool it 2·2° below its moist air value. The observations made on the skin of the thigh gave an

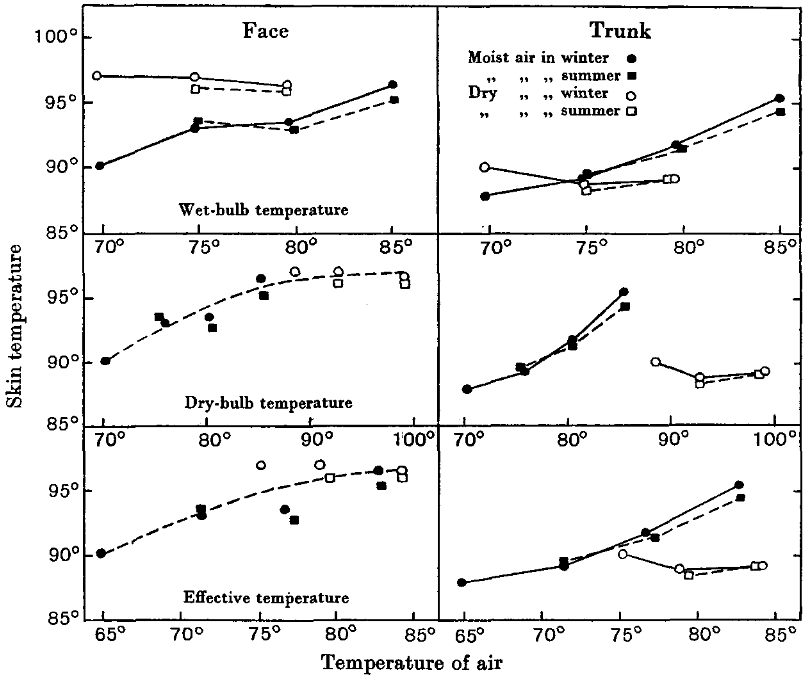

Fig. 9. Skin temperature in relation to air temperature and humidity.

Table VI. *Mean skin temperature in relation to humidity and to season.*

		Air temperature		Subject W.			Subject V.		
		Dry bulb	Wet bulb	Face	Trunk	Difference	Face	Trunk	Difference
Season		° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.
Moist air experiments in	Winter	80·4	79·6	93·6	91·8	1·8	93·0	92·0	1·0
	Summer	80·5	79·9	92·9	91·4	1·5	92·2	91·8	0·4
Dry air experiments in	Winter	99·0	79·6	96·5	89·3	7·2	94·9	90·3	4·6
	Summer	99·1	79·5	96·0	89·4	6·6	93·9	89·3	4·6
Difference between dry air and moist air experiments				+ 3·0	− 2·2		+ 1·8	− 2·1	

intermediate result, the skin surface having the same temperature at both humidities.

No attempt was made to measure the average surface temperature of the whole skin of the body, so a mean of the observations made on face, chest, side and thigh is the best index available. This is plotted in Fig. 10, in relation to the dry-bulb scale (for subject W., in winter). It will be seen that the skin temperature rose gradually with rise of moist-air temperature, but there was a break of continuity on passing to the dry-air observations. Moreover, these observations showed no rise of skin temperature with rise of dry-bulb air temperature. This must have been due to the inadequacy of the skin areas tested, for we know that the skin surface, taken as a whole, must warm up as the air temperature increases, and induce the observed rise in body temperature and pulse rate. The actual pulse rates and body temperatures observed are plotted in the lower portion of the figure for comparison, and it will be seen that the pulse rate shows the same break of continuity on passing from the moist-air to the dry-air experiments, though the body temperature does not show it much.

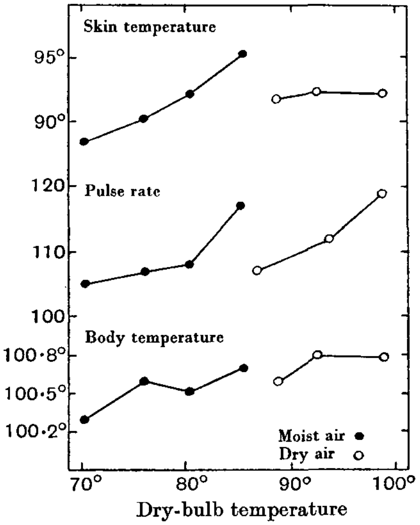

Fig. 10. Skin temperature, pulse rate and body temperature in relation to dry-bulb temperature of the air.

Previous observations. Yaglou and his colleagues (cf. Yaglou, 1927) made many observations on skin temperature, and they found that it rose with increase of effective temperature, the rise (at temperatures below 90°) being more rapid for the skin of the cheek than for that of the abdomen. They do not appear to have compared moist air and dry air results. Campbell and Angus (1928) found that in three resting subjects the cheek temperature was more than 3° higher when they were in dry air than in moist air of the same wet-bulb temperature. Liese (1930) observed that sweating might cool the skin surface, for he found that the forehead temperature of a subject who was exposed to an air temperature of 83° was 2° lower when he was performing mechanical work than when he was at rest.

(5) *Energy expenditure.*

The influence of air temperature and humidity on energy expenditure and on capacity for work is a question of great practical importance, and we expended a large amount of time in investigating it. We found that within the temperature range tested there was only a small effect on energy expenditure, but it does not follow for a moment that industrial workers who have to pursue their occupation for 44–48 hours a week under similar atmospheric conditions would be just as little affected. In our experiments subject W. did a fixed amount of mechanical work at a fixed rate regardless of the fatigue induced, and as he did this work only for 3 hours at a time on alternate days he was able to recuperate between the experiments. If he had worked every day for 8 hours, like industrial workers, he would have had to reduce the work done in hot and dry air to a much greater extent than that done in relatively cool and moist air, in order to counteract the greater fatigue induced. Hence our observations on energy expenditure have to be considered in conjunction with those of the fatigue induced, which are discussed in a later section.

Experimental procedure. The gas bags into which subject W. breathed were emptied as soon as possible after the completion of the experiments in the air-conditioning room, two samples being taken and analysed in each case. Samples were also taken of the air in the air-conditioning room at the times of collection of the first and last bags of expired air, as the carbon dioxide in the room steadily increased during the course of the experiments, because of the limited amount of air drawn into the circuit. Owing to the investigators having already been in the room for short periods before the main experiment began, the CO_2 amounted to 0·080 per cent., on an average, at the time of collection of the first bag of expired air, and it rose to 0·185 per cent. at the time of collection of the last bag, 2½ hours later. As the analyses made on different days agreed well with one another, it was thought best to make the same corrections in all experiments, it being assumed that the percentage of CO_2 in the inspired air rose at a steady rate during the course of the 3 hours. The CO_2 in the expired air fell slightly during the course of the 3 hours, for it averaged 4·31 per cent. in the first half hour and gradually fell to 4·21 per cent. in the last half hour (in the winter experiments). From the data recorded in Tables I and II it will be seen that it was very steady in the different experiments, whilst the respiratory quotient was likewise very steady.

Oxygen consumption. The gross volume of oxygen consumed per minute, reduced to normal temperature and pressure, is recorded in Tables I and II, as an average for 3 hours. It always dwindled during the course of the experiment, as can be gathered from Fig. 11, which shows the mean oxygen consumption in the experiments made at a wet-bulb temperature of 80°. It will be seen that the oxygen consumption reached a minimum during the last hour, so the experiments lasting 2½ hours instead of 3 hours were corrected to a 3-hour average on the assumption that the rate of fall during the missing half hour would have been the same as that observed in the full 3-hour experiments. The cause of the fall is uncertain. It may have been due partly to the diminishing influence of the small quantity of food (biscuits) eaten shortly before the experiment began, but it has been suggested to us by Prof. A. V. Hill that the subject of experiment, as he was unfatigued at first, may have made quicker and more energetic muscular movements over his step climbing than he did later on when he was fatigued. It might be thought that a man pedalling on a bicycle ergometer, as in Moss' experiments (1925), would be more likely to work at an even pace throughout than a man engaged in step climbing. However, an average of Moss' two series of experiments shows 6 per cent. less oxygen consumption in the second hour of work than in the first hour.

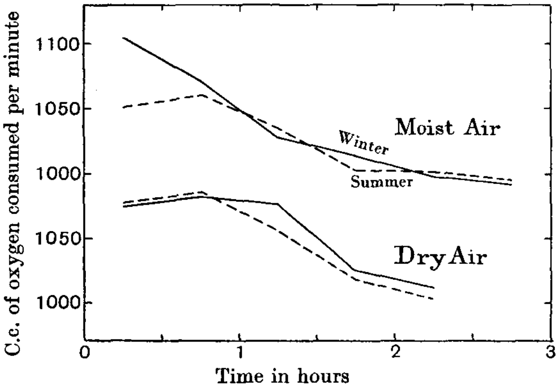

Fig. 11. Oxygen consumption in relation to humidity and to season.

The summer results corresponded well with the winter ones, except that the oxygen consumption was rather smaller, owing to the subject being lighter in weight. It is therefore better to compare them in terms of gross efficiency. This was determined by assuming that 427 kg. m. of work are equivalent to 1 calorie, the calories used being calculated from the respiratory quotient and the oxygen consumption in accordance with the relationships gives by Zuntz and Schumburg (1901). It will be seen from Tables I and II that the subject did 14,240 to 14,580 kg. m. of work per hour in winter, and from 13,800 to 14,000 kg. m. in summer. In winter he weighed about 137 lb. (62·1 kg.) when stripped, and in summer 132 lb. (59·9 kg.). He is 5 ft. 5 in. in height.

Mechanical efficiency. The variations in efficiency at different temperatures were very small, and in order to increase their reliability it was thought best to average the winter and summer values, as they corresponded closely. Air temperature had a small but distinct influence on efficiency, as can be gathered from Table VII and from the curves in Fig. 12. We see that when the data were plotted on the wet-bulb scale efficiency gradually diminished at temperatures above 70° or 75°, that attained in dry air being slightly lower than in moist air. In the numerous observations made at a wet-bulb temperature of 80°, the mean efficiency was 13·25 per cent. in moist air and 13·05 per cent. in dry air, or 1·5 per cent. less. This difference is not statistically significant.

Table VII. *Gross mechanical efficiency in relation to humidity and season.*

Moist air						Dry air					
Air temperature						Air temperature					
Dry bulb ° F.	Wet bulb ° F.	Effective °	Winter	Summer	Mean	Dry bulb ° F.	Wet bulb ° F.	Effective °	Winter	Summer	Mean
70·2	69·8	64·9	13·4	—	—	88·8	69·7	75·1	13·5	—	—
75·9	74·8	71·3	13·5	—	13·43	92·6	74·8	79·0	13·1	—	13·18
75·6	74·8	71·3	—	13·35		92·7	74·9	79·5	—	13·25	
80·4	79·6	76·7	13·4	—	13·25	99·0	79·6	84·2	13·2	—	13·05
80·5	79·9	77·2	—	13·1		99·1	79·5	84·2	—	12·9	
85·4	85·0	82·7	12·65	—	12·78	—	—	—	—	—	
85·4	85·0	82·9	—	12·9		—	—	—	—	—	
Means of comparable data			13·18	13·12					13·15	13·08	

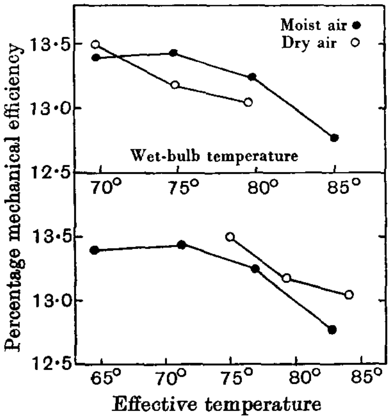

Fig. 12. Gross mechanical efficiency in relation to air temperature.

When the results were plotted on the dry-bulb scale the lack of correspondence between the moist-air and the dry-air results was more marked; but it can be seen from Fig. 12 that when they were plotted on the effective temperature scale the agreement was rather better than given by the wet-bulb scale. The effective temperature scale makes too great an allowance for dry-bulb temperature, though it is evident that an allowance of some sort ought to be made.

Previous observations. No previous observations appear to have been made with the special object of measuring mechanical efficiency in relation to humidity, but several investigators have determined the effect of temperature. Hill and Campbell (1922) made observations on a subject who pedalled a bicycle ergometer for a period of about 40 min. at a temperature of 41–96° F., and they observed practically no change in the efficiency of the work performed. Moss (1925) found that his subject, when pedalling a bicycle ergometer, had a slightly lower oxygen consumption at very high air temperatures than at medium ones, but his subject pedalled at an air temperature of about 77° on the first day and gradually worked upwards to the higher temperatures. He probably got more accustomed to the work, and performed more efficiently, for we ourselves found that in our preliminary experiments mechanical efficiency was substantially lower than it was later on. For instance, it can be seen from Table II that in the first experiment of the summer series (No. 33) the mechanical efficiency of the subject was only 12·5 per cent. as compared with 13·1 per cent. in the subsequent five experiments made under the same atmospheric conditions.

The efficiency of a subject doing 10,000–20,000 kg. m. of work per hour on a bicycle ergometer has been investigated by Yaglou (1931) at effective temperatures of 40–100°. The mean curves indicate that maximum efficiency was reached at a temperature of about 60°, the gross efficiency amounting to 12·4 per cent. for 10,000 kg. m. of work, 15·3 per cent. for 20,000 kg. m., and 18·4 per cent. for 30,000 kg. m. At higher temperatures the efficiency fell off at about the same rate as was observed by ourselves. It will be noted that the gross efficiency observed by Yaglou was about the same as that observed by us, though work on a bicycle ergometer generally gives a higher figure. For instance, Benedict and Cathcart (1913) found the maximum efficiency of six individuals to vary from 17·8 to 21·2 per cent. Step climbing would be expected to show a lower efficiency than work on a bicycle ergometer, as it makes no allowance for the work done by the subject in stepping down after each step up.

Dill and his colleagues (1931) got their subjects to do about 40,000 kg. m. of work on a bicycle ergometer for an hour or less at temperatures of 56 and 93° F., the relative humidity being about 50 per cent. in each case. Single experiments were performed by each of five subjects under each set of conditions, and the mean mechanical efficiency was 20·0 per cent. in the hot room, and 19·8 per cent. in the cold room.

In our experiments we were unable to ascertain the resting metabolism of the subject at the time as it would have been too tiring for him, but in the last experiment recorded in Table I the (unclothed) subject rested nearly horizontally for a period of 3¼ hours at a temperature of 100·2° (d. b.) and 80·4° (w. b.). His oxygen consumption was ascertained after 35–190 min., and it averaged 358 c.c. per min. Numerous observations were made on the normally clad subject at an air temperature of about 63°, and they showed that after he had been sitting upright for a period of 23 min. his oxygen consumption amounted to 307, 290, 287 and 288 c.c. respectively in the next four half-hour periods. These figures are the means of three sets of observations, and they indicate a resting metabolism 19 per cent. lower than that observed in the hot room. In another series of observations made at an air temperature of 66° the subject stood or sat quietly for 20 min. before a 5-min. sample of expired air was collected. Eight standing observations gave an average oxygen consumption of 347 c.c. per min., and eight sitting observations one of 328 c.c.

(6) *Sweating.*

The great influence which the humidity of the air exerts upon sweating is well known to everyone. In our experiments the sweating was bound to be considerable because of the high temperatures at which they were made. The loss of moisture from the skin and lungs was ascertained by weighing the stripped subjects immediately before and after each experiment, and making an allowance for the water drunk. This water was warmed to body temperature, so that it should not exert a direct cooling effect, and the subjects drank as much as they felt inclined to do during the 5-min. rests. The amount was almost always less than that lost by sweating, especially at high temperatures. The weight of water drunk per hour by subject W. is recorded in Tables I and II, and also the loss of body weight. The figures recorded show that he lost from 7·2 to 23·8 oz. of moisture per hour, whilst subject V. lost 1·3–14·0 oz. According to the observations of Campbell and Angus (1928) 9–16 per cent. of the total moisture lost (by resting subjects) is derived from the lungs.

Temperature and humidity effects. The relationship between loss of moisture and air temperature is plotted in Fig. 13, on the three scales. It will be seen that in both subjects it increased fairly regularly as the temperature rose, but the upper set of curves, which relate to the wet-bulb scale, show that the loss of moisture was about twice as great in dry air as in moist air of the same wet-bulb temperature. In the middle set of curves the results are plotted on the dry-bulb scale, and it will be seen that there is a marked break of continuity in the moist air and dry air results, especially in subject W. The lower pair of curves show that on the effective temperature scale there is a fair correspondence of moist-air and dry-air results, especially in subject W. Moreover, the summer results are in good agreement with the winter ones.

Acclimatisation factor. The experimental results are necessarily rather irregular because of the factor of acclimatisation. The existence of this factor is indicated by the results plotted in Fig. 14, which relate to consecutive experiments made at a wet-bulb temperature of 80°. In the four dry-air experiments made in winter (Nos. 19–22) the weight of moisture lost by subject W. gradually increased from 17·8 to 21·2 oz. per hour, whilst in the six consecutive experiments made in summer it increased from 17·8 to 23·2 oz. Following immediately on the four winter experiments in dry air, three were made in moist air, and the loss of moisture observed in the first of them was 18·7 oz., or *more* than in the first of the dry-air experiments. In the next two experiments it fell gradually to 11·8 oz., or to half the maximum loss observed in dry air. In the summer six consecutive experiments were made in moist air, and the mean loss, in the last three, was 10·2 oz. per hour. The maximum of 23·2 oz. observed in the subsequent dry-air experiments suggests that if the subject had been thoroughly adapted to his environment he would have lost about three times more moisture in dry air than in moist air. Subject V., on the other hand, showed no sign of acclimatisation to dry air, and but little to moist air.

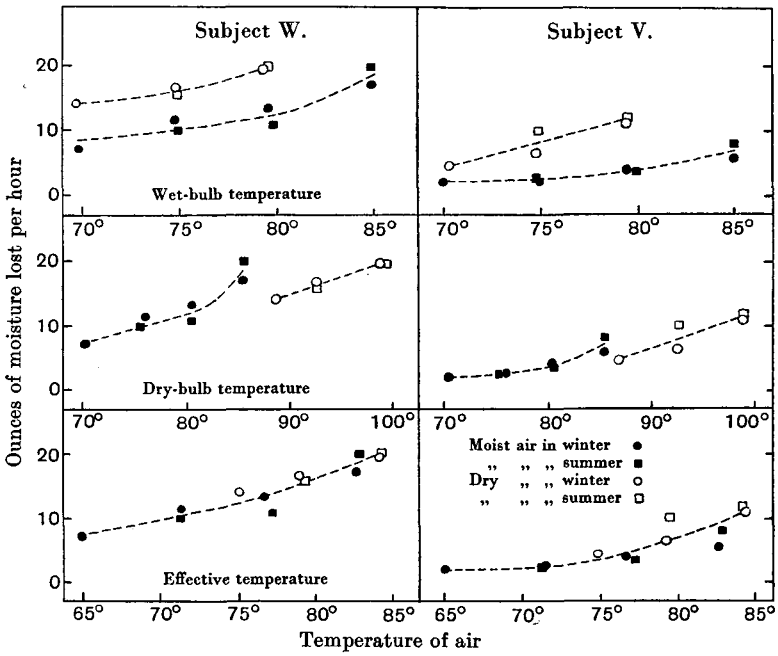

Fig. 13. Loss of moisture in relation to air temperature and humidity.

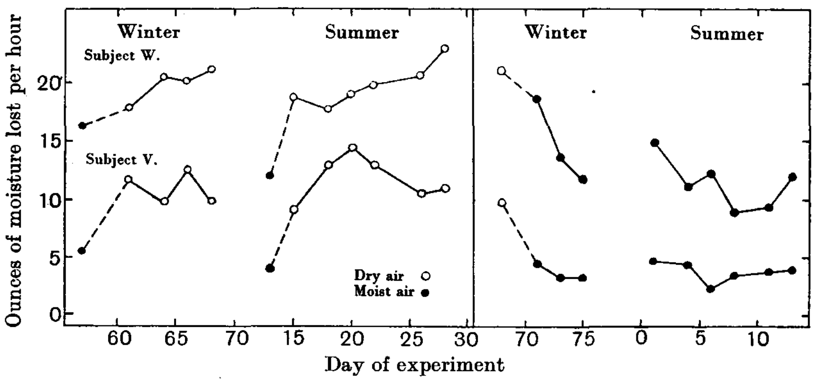

Fig. 14. Loss of moisture in consecutive experiments made in dry and moist air.

The effect of acclimatisation on sweating has been previously pointed out by Moss (1923), who found that when two unacclimatised men did a shift's coal loading in a mine at a temperature of 82° (d. b.) and 77° (w. b.), they lost 13·4 oz. per hour in weight, on an average, whilst five acclimatised miners lost 23·9 oz. However, one of the acclimatised miners lost less than one of the unacclimatised men, and it does not appear that the two groups of men did the same amount of mechanical work, so the evidence is not conclusive.

(7) *Fatigue.*

Though all the physiological reactions above described showed some response to the differences of air temperature and humidity investigated, none of them, except the sweating, were of so marked a character as to suggest that the heavy work performed threw much strain on the subject, and that the various atmospheric conditions would induce great differences in the fatigue experienced. In actual fact, the fatigue varied much more than the other reactions. Many of the 3-hour experiments proved very tiring, especially to subject W. Indeed, the experiments in dry air at a wet-bulb temperature of 80° and in moist air at 85° had to be cut down to 2½ hours. Even then, subject W. found them more tiring than when he was making observations in a coal mine at a temperature of 80° (d. b.) and 72° (w. b.) for the greater part of five shifts a week. The fatigue was probably due in large part to the same muscles being used throughout in the step climbing, in contrast to the frequent changes of muscular movements which would be made in mine work.

Method of estimating fatigue. Fatigue is admittedly not capable of exact measurement, but even the rough qualitative method employed gave striking results. The subjects carefully assessed their sensation of fatigue at the end of each experiment in accordance with the following scale, and they were convinced that their assessment was correct to within about half a point.

Slightly tired	1
Moderately tired	2
Tired	3
Very tired	4
Excessively tired	5

Average results. The estimates of the fatigue of subject W. are recorded in the last column of Tables I and II, and the means for both subjects are plotted in Fig. 15 in relation to the three temperature scales. In the experiments lasting 2½ hours a + is added to the estimated value in the tables, and in the figure an extra 0·5 unit was added in order to bring them into line with the full 3-hour experiments. In subject W. the fatigue experienced increased from a value of 2 (or "moderately tired") at the lowest temperature to 5+ (or more than "excessively tired") in moist air at 85°, whilst in subject V. it ranged from 1·5 to 4+.

We see from the upper set of curves in Fig. 15, which are plotted on the wet-bulb scale, that at all temperatures dry air induced about one unit more of fatigue than moist air. The summer results corresponded with the winter ones, though the fatigue induced was slightly less. The lack of continuity of the moist-air and dry-air results is very marked when they are plotted on the dry-bulb scale, but there is good agreement when they are plotted on the effective temperature scale.

There could be no doubt whatever that at a given wet-bulb temperature dry air induced more fatigue than moist air. This result appears to be contrary to the statement made at the beginning of this paper about the effects of hot and dry seasons and of rainy seasons in the tropics, but we have not been able to ascertain whether the wet-bulb temperature during the rainy seasons is similar to that experienced in the hot and dry seasons. Supposing that it is no higher, it is possible that the disagreement of our results depends largely on clothing. When a clothed person is in warm moist air the perspiration from his skin evaporates but slowly, and he feels unpleasantly damp, but in dry air the evaporation is so much more rapid that he usually feels his skin and clothing to be dry. In our experiments, however, the question of discomfort from clothing did not enter, and we scarcely noticed whether the skin was moist or dry. The

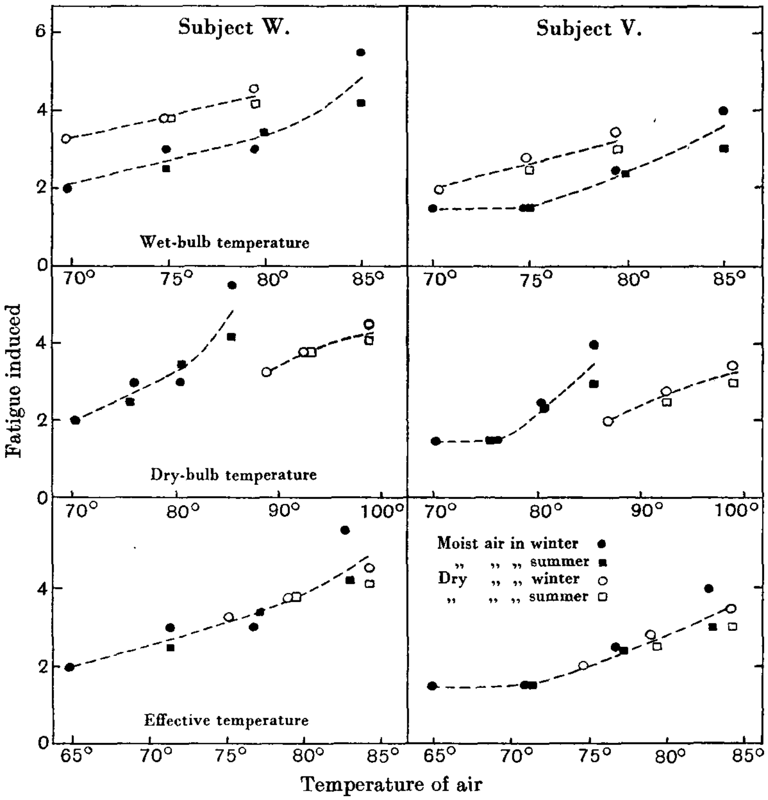

Fig. 15. Fatigue in relation to air temperature and humidity.

coal miner would be equally unaffected by clothing, as he suits himself to his conditions of work. In very hot mines he works stark naked or wears only thin drawers.

Another explanation of the contradiction between our results and general experience may depend on their brief duration. Though a 3-hour stay in moist air proved less trying than a similar period in dry air, a stay of many hours or days might have the reverse effect.

It is evident that further observations on thoroughly acclimatised subjects ought to be made before our results are accepted as genuine. Unfortunately, it is very difficult to make comparable experiments on subjects such as coal miners. Very few deep coal mines exist in which the air is moist in some of the workings and dry in others. Even if they were available, it would be difficult to transfer the men from one set of atmospheric conditions to the other, as in most mines they keep to the same working place.

V. GENERAL CONCLUSIONS.

(1) *Correspondence between reactions and temperature scales.*

We have seen that when the various physiological reactions of the two subjects to moist air and dry air were considered in relation to the three temperature scales, they always failed to show correspondence with the wet-bulb scale. When considered in relation to the dry-bulb scale they also failed, except in respect to the skin temperature of the face. In subject W. this agreed well with the dry-bulb temperature scale, and in subject V. moderately well. The reactions evidently did not, as a whole, conform either to wet-bulb temperature or to dry-bulb temperature, but to something between the two, and we saw that the effective temperature scale afforded a fairly correct combination for the majority of the physiological reactions tested, especially in the winter experiments. In subject W. (in winter) the pulse rate, body temperature, skin temperature of face, loss of sweat and degree of fatigue, all agreed well with the scale, and only the skin temperature of the trunk showed a total lack of agreement, and this for obvious reasons. The energy expenditure did not agree well, as it showed too great an allowance for dry-bulb temperature, but it certainly indicated that an allowance of some sort must be made.

An allowance for dry-bulb temperature also held for the pulse rates and body temperatures observed in the summer and, as already pointed out, these results not only indicated the effects of acclimatisation, but they strongly suggested that if acclimatisation had been more perfect the allowance for the dry-bulb factor would be smaller. It seems unlikely, however, that it would sink to zero except at very high temperatures, for the skin surface of a man working at moderately high temperatures is not covered all over with a layer of moisture, and in that case the dry-bulb temperature of the air is bound to have some effect on the temperature of the body, and consequently, on the pulse rate and other reactions.

(2) *Observations on coal miners.*

Observations on the working capacity of miners in various mines which differed greatly in humidity have been made by Bedford and Warner (1931). As a measure of working capacity they observed the rest pauses taken spontaneously by the men, and altogether 304 men, working at five collieries, were kept under observation. In air at a dry-bulb temperature of about 81° the voluntary rests varied from 5·5 min. per hour, in air less than 60 per cent. saturated, to 7·0 min. in air 70 to 98 per cent. saturated; but the air velocity was less in the more humid mines, and it was concluded that relative humidity had no definite effect. The coefficients of correlation between duration of rest pauses and various atmospheric conditions showed that the amount of time taken for rests was more closely associated with the dry-bulb factor than with the wet. With wet kata cooling power constant, a reduction in the dry kata cooling power was accompanied by an increase in the length of time taken voluntarily for rests; but with a constant dry kata cooling power variations in the wet kata had no effect. The correlation with effective temperature was intermediate.

The method of estimating working capacity by means of the rest pauses taken, though not a good one, is the best available, and in virtue of the large number of men investigated there can be no doubt that the dry-bulb temperature of the air had a distinct influence on their efficiency. Whether it is of sufficient importance to justify the artificial humidification of the air in a dry mine—as suggested by Yaglou—is doubtful. Bedford and Warner (1931) made a direct experiment on local air conditioning by this means, and when their apparatus was working close to the coal face they got a reduction of 7·8° F. in the dry-bulb temperature, but after traversing 35 yards of the face the cooling effect was reduced to 1·9°.

It is possible that artificial humidification might be worth while in mines where the air is very hot and dry and the relative humidity very low. More likelihood of success would appear to be found in the stokeholds of steamers, where the temperature sometimes rises to 130° F. or more, and where a system of artificial humidification could easily be installed. The work of the stokers is often excessively fatiguing, and any improvement in the atmospheric conditions would greatly enhance their comfort and efficiency.

(3) *Air-conditioning by compression.*

A promising method of air conditioning has recently been described by Egan (1931). The mine air at the pit bottom is compressed by a powerful pump, and the heat generated by adiabatic compression is got rid of by water cooling, and much of the contained moisture is condensed. The subsequent expansion of the compressed air causes pronounced cooling. The plant employed in a South African mine is so powerful that when 3000 c. ft. of air saturated at 95° were compressed and cooled to 80° every minute, the decompressed air discharged had a temperature of only 32°. It was allowed to mix with four times its volume of the hot mine air, and it is said to have greatly improved the atmospheric conditions experienced by the 97 men in the working places served by the machine.

The data described in this paper indicate that, even at a constant air velocity, the effective temperature scale adduced by Yaglou and his colleagues is only moderately accurate, owing to the effects of acclimatisation. At different air velocities the scale shows further inaccuracies, for Yaglou and Drinker (1928) state that the data relating to air velocities of 20–150 ft. per min. need revision, as they were estimated by interpolation and not directly. It follows that the scale, though a great improvement on other scales, needs considerable revision.

VI. SUMMARY.

The physiological reactions of two subjects were investigated in air at a temperature of 70–100° F., and of 40–96 per cent. relative humidity. The experiments lasted 3 hours, and one of the subjects performed mechanical work (step climbing) at the rate of 14,000 kg. m. per hour.

The pulse rate was about 10 beats greater in dry air than in moist air of the same wet-bulb temperature. The winter observations agreed well with the effective temperature scale, but did not agree with the wet bulb, the dry bulb or the kata-thermometer scales.

Acclimatisation effects showed themselves in experiments made at a dry-bulb temperature of 87° F. or more, but only very slightly in those made at 81° or less. Acclimatisation was fairly well marked in the summer, the pulse rate being 5 to 10 beats less than in the winter, and no longer agreeing with the effective temperature scale.

The body temperature corresponded with the pulse rate, for it was 0·3–0·6° F. higher in dry air than in moist air of the same wet-bulb temperature, and was 0·15° lower in summer than in winter. The winter observations agreed well with the effective temperature scale.

The skin temperature of the face was found to depend on the *dry-bulb* temperature of the air, but that of the trunk showed no agreement with any of the scales. In moist air it was 1° F. lower than that of the face, and in dry air, 6° lower, owing to the cooling effect of increased sweating.

The gross mechanical efficiency fell off slightly at temperatures above 70 or 75° F. It was affected by the dry-bulb temperature of the air as well as the wet bulb, but not to the extent indicated by the effective temperature scale.

The weight of moisture lost by sweating corresponded well with the effective temperature scale. It increased gradually in consecutive experiments made in dry air, and diminished in those made in moist air.

The degree of fatigue experienced in dry air was considerably greater than in moist air of the same wet-bulb temperature, and it corresponded with the effective temperature scale.

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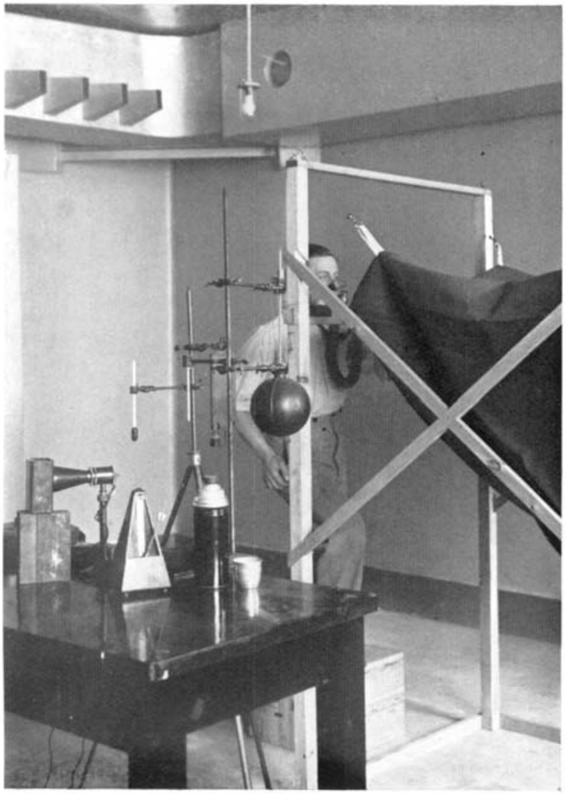

Subject step climbing in the air-conditioning room.