VENTILATION OF IMPERMEABLE CLOTHING

THE EFFECTIVENESS OF THE AMBIENT ATMOSPHERE IN VENTILATING COVERALLS WORN IN HOT AND HUMID CONDITIONS

BY

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In the handling of highly concentrated liquids used as oxidants in guided weapons or for protection against highly toxic gases and liquids the Services require a completely impermeable coverall which can be worn for periods of up to two hours. It is well known that wearing such clothing restricts evaporative cooling and may cause collapse from heat stroke. Robinson and Belding (1948) place a limit of one hour at 75° F. and 25 minutes at 85° F. on the time of wearing such a suit. Under tropical and desert conditions the problem of cooling is particularly difficult and some form of ventilation becomes essential. Since the beginning of the century patents have been issued for devices to relieve this heat stress by circulating cooled air under clothing. None of these devices, however, is practicable for use under Service conditions in remote areas nor do they meet a requirement that the protective clothing should be self-contained, *i.e.*, it must not be attached to a remote source for cooling or dehumidifying.

It seemed, therefore, that any practical method of ventilation would necessarily be based on the use of ambient atmospheres, but no information was available about this. Although such a method cannot maintain temperature equilibrium in a wearer, except under mild conditions, it was felt desirable to ascertain the degree of alleviation which might be obtained under various conditions. To this end a study has been made of the physiological strain produced in men performing light work in a range of simulated climatic conditions while wearing impervious suits through which ambient air was pumped at controlled rates.

A practical garment would need a portable pump to supply the air, and the present data will be used in the development of a suitable pump.

Experimental

Subjects.—Nine fit young men of ages ranging from 18 to 25 years volunteered for the trials. Two were Naval ratings, six were men from these laboratories, and one was an Army officer from the Weapons Research Establishment, Woomera. Seven were used in each trial, five as subjects and the other two as controls.

Clothing.—A subject wearing the complete equipment is shown in Fig. 1.

The impervious coverall was fabricated from PVC film. All joints were welded and the material drawn in at the wrists and ankles by elastic. A slide fastener covered by a flap of the PVC material allowed the front of the garment to be opened. The neck-band was fitted with a drawstring tied to effect a seal as airtight as

FIG. 1.—Subject and control dressed for the trials.

FIG. 2.—Subjects resting in chamber.

possible commensurate with the comfort of the wearer. The suit was worn over short cotton drawers and a cotton athletic singlet. The average free space between the coverall and the subject was approximately $1\frac{1}{2}$ ft³.

The headgear consisted of a light-weight aluminium helmet with a clear plastic visor of 0.020 in. cellulose acetate extending round the head from the helmet brim almost to the shoulders. The visor carried a skirt of PVC film which draped over the shoulders to give a partial seal with the suit. Tubes attached to a mouth gag enabled the subjects to breathe chamber air and exhale outside the hood. Bands of cotton fabric were worn round the forehead to keep sweat out of the eyes.

Fabric-lined PVC gloves and ankle-length rubber boots with light woollen socks were worn. Gaiters of PVC film were worn over the boots and tucked up under the trouser legs to ensure that no gap existed between the trousers and the top of the boots.

A remote pump supplied ventilating air to a metal manifold in the back of the suit, from which it was distributed to six points within the suit by means of rubber tubing of $\frac{1}{4}$ in. internal diameter. Air was taken to each wrist and ankle, the small of the back, and the crown of the head. Approximately equal volumes were released at each point. The air escaped through two $\frac{1}{2}$ in. diameter holes in the shoulders of the suit.

A small thermoelectric psychrometer (see Appendix 1) was located in the left breast position for measurement of temperature and humidity within the coverall at intervals of 15 minutes throughout each trial. The suction tube and three thermocouple leads from this unit are visible in Fig. 1.

The total weight of the suit, including a small Dewar flask of ice for the thermocouple cold junction, was 4 lb. The other accessory equipment, including rubber boots and gloves, underwear, and headgear, weighed an additional 6 lb.

The subjects who acted as controls wore only cotton singlets and drawers, boots, and socks.

Chamber.—Trials were conducted in a well-insulated stainless steel chamber of 100 m³. capacity, designed for trials with human subjects under controlled climatic conditions. During the trials wet- and dry-bulb and globe thermometer readings were taken at regular intervals. Air to ventilate the coveralls was drawn from the chamber by external pumps and passed to the subject through flexible non-kinking rubber attached to the manifold in the suit. The temperature and humidity of the pumped air were the same as those of the air in the chamber. Pumping rates of 5, 10, and 15 ft³/min. were used.

Nature of the Exercise.—The subjects entered the chamber and the air lines and thermocouple leads were attached as soon as possible. They then rested for one hour in a sitting position (Fig. 2). Reading was permitted during this period and most subjects did so. The second hour was divided into alternate five-minute periods of light work and rest. During each work period the subjects stepped on to and down from a 9 in. step 100 times (Fig. 3), so that each person's work output in the hour was about 75,000 ft. lb. After the final rest period the subjects left the chamber.

Simulated Climatic Conditions.—The tests were carried out at temperatures ranging from 70° to 110°F. and relative humidities of 40 to 80%. In order to compare various environments it is necessary that the combined effects of the separate factors be expressed in terms of a single index. The corrected American Society of Heating and Ventilating Engineers' effective temperature scale for semi-nude persons (Bedford, 1946) was found to be the most appropriate index for this purpose under the conditions of the test.

FIG. 3.—Subjects exercising in chamber.

Physiological Observations.—The following physiological data were recorded at the beginning and end of each trial.

(a) Rectal temperatures by means of clinical thermometer; (b) total sweat loss by difference in nude weight; (c) evaporated sweat loss by difference in clothed weight; (d) unevaporated sweat by increase in weight of clothing after wearing and also by difference between (b) and (c); (e) pulse rate was also taken at intervals during each trial; (f) subjects' comments on their reactions.

Pulmonary evaporative loss was not considered to be of sufficient importance to require separate recognition.

Physiological Response.—Some workers have utilized a single physiological measurement as an index; thus Craig, Garren, Frankel, and Blevins (1954) considered rectal temperature the best estimate of heat storage and consequently of heat tolerance, while McArdle, Dunham, Holling, Ladell, Scott, Thomson, and Weiner (1947) considered the sweat rate alone an adequate index of heat stress. Under conditions of extreme heat McConnell, Houghten, and Yagloglou (1924) found the pulse rate to be the best index of strain. However, Newburgh (1950), Ladell (1955), and others have shown that it can be misleading to judge a subject's response on any one factor. They quote cases of disabling heat exhaustion without a significant rise in rectal temperature.

The better known indices of strain, for example, the "index of physiological effect" of Robinson, Turrell, and Gerking (1945) or the "thermal acceptance ratio" devised by Plummer, Ionides, and Siple (1945), include skin temperature as a component. As our work employed temperatures well into the evaporative cooling zone where skin temperatures are a poor measure of heat stress, such measurements were not taken. We therefore adopted an index modified from Robinson and defined as follows:—

$$I = T + S + P$$

where I = physiological index,
 T = change in rectal temperature ($^{\circ}\text{F.}$)
 S = sweat loss (lb.) and
 P = final pulse rate per second, *not* per minute.

Results and Discussion

The mean values of the various observations taken during each test, together with the effective temperatures and indices of physiological strain calculated as discussed above, are shown in Table 1.

Standard deviations were not calculated as the mean values given covered only five observations. No individual result, however, varied from the mean values quoted by more than 75% of the increase in rectal temperature, 60% of the total sweat loss, or 25% of the final pulse rate.

In trials 1 to 10 the head was not ventilated, but because of some stated discomfort within the headgear, part of the ventilating air was diverted to the top of the head in later trials. Although the subjects stated that this afforded some degree of relief at the higher temperatures, there was no change in the physiological response as measured by the index.

The various indices are plotted on a logarithmic scale against effective temperature in Fig. 4. It will be noted that the sets of points corresponding to each rate of ventilation and to the response of the controls are adequately fitted with straight lines. Further, these lines (least squares fit) are almost parallel with that for the 10 ft.³/min. ventilating rate equidistant from those for the 5 and 15 ft.³/min. rates.

TABLE 1
EXPERIMENTAL CONDITIONS AND MEAN OBSERVATIONS ON SUBJECTS

Trial No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Atmospheric temperatures during the trial (°F.)																					
Dry bulb	72	83	93	92	92	101	102	83	82	103	92	101	110	91	89	110	82	91	81	93	90
Wet bulb	66	71	78	81	85	84	82	73	75	83	84	82	88	76	80	86	73	74	71	80	81
Effective	69	76	83	84	87	88	88	76	78	89	86	87	93	81	83	91	76	80	75	84	84
Relative humidity (%)	75	57	55	61	75	50	45	64	72	45	73	46	42	50	62	39	64	44	60	59	68
Air flow through suit (ft. ³ /min.)	5	5	10	10	10	10	10	5	5	10	10	15	15	5	5	15	15	15	10	15	5
Increase in rectal temperature (°F.)																					
Subject	0.8	1.0	1.5	2.3	2.3	3.1	3.2	0.4	1.3	3.1	1.8	1.9	3.9	1.6	2.1	3.0	0.3	0.7	0.4	1.3	2.3
Control	0.4	0.1	1.0	0.5	0.8	1.1	0.9	0.1	0.2	1.8	1.0	0.6	2.1	0.2	0.3	2.4	0.3	0.4	0.2	0.5	0.2
Final pulse rate per minute																					
Subject	98	114	116	120	129	134	131	99	100	138	118	122	142	113	116	126	81	94	86	104	131
Control	88	93	114	96	94	96	106	93	91	113	98	94	123	89	105	102	96	82	84	93	76
Total sweat loss (lb.)																					
Subject	0.6	1.3	2.0	2.1	2.5	3.0	3.1	1.2	1.1	3.5	2.6	2.9	3.3	2.9	2.7	2.8	0.9	1.1	1.0	2.2	1.9
Control	0.2	0.8	1.0	1.3	1.5	2.0	1.9	0.5	0.7	1.8	1.6	1.8	2.8	1.2	1.3	3.4	0.8	0.9	0.7	1.5	1.3
Physiological index																					
Subject	2.8	4.2	5.4	6.4	6.9	8.3	8.4	3.2	3.8	9.0	6.3	6.8	9.5	6.4	6.7	7.9	2.5	3.4	2.8	5.2	6.4
Control	2.2	2.2	3.8	3.3	3.8	4.6	4.5	1.8	2.2	5.5	4.2	3.9	7.4	2.7	3.1	7.4	2.6	2.6	2.3	3.4	2.8
Temperatures within suit at the beginning of the work period (°F.)																					
Dry bulb	84	89	93	94	95	98	98	90	89	97	95	98	101	92	94	100	89	93	88	93	93
Wet bulb	74	82	82	83	91	92	92	78	83	90	91	91	94	79	91	92	78	88	78	86	91
Effective	78	84	85	86	92	93	93	82	85	92	92	93	95	83	92	94	82	89	81	88	91
Effective temperature within suit at the end of the trial (°F.)																					
Subject	82	92	94	93	94	98	98	91	90	98	96	94	101	96	96	98	83	89	82	92	95
Control	a	a	a	a, b	a	a	a	a	a	a	a	b	c	b	b	b, d	b	b	b	b	b

a—head was not ventilated.

b—only four subjects used.

c—subjects could not complete the full work and number of steps ranged from 420 to 500.

d—work limited to 500 steps.

The curves show that each additional 0.5° F. effective temperature would necessitate a 1 ft.³/min. increase in ventilation rate in order to maintain the physiological index at a steady level. Further, this figure is independent of the index within the range 2 to 10. On the other hand, at any given ventilation rate within the range 5 to 15 ft.³/min. the effect on the physiological index of increasing the effective temperature becomes more marked at higher temperatures as shown in Table 2.

TABLE 2
EFFECT OF CHANGE IN EFFECTIVE TEMPERATURE ON PHYSIOLOGICAL INDEX UNDER STANDARD WORKING CONDITIONS

Ventilating Rate (ft. ³ /min.)	Change in Physiological Index for Various Changes in Effective Temperature			
	70-75°F.	75-80°F.	80-85°F.	85-90°F.
5	1.2	1.8	2.4	—
10	1.0	1.4	2.2	3.2
15	—	1.2	1.8	2.4

Some difficulty was experienced in attempting to set a desirable upper limit to physiological strain as measured by the index. For example, the indices of the more copious sweaters tended to be higher than those of the other subjects. In one trial, an index of 9 was recorded, although the subject reported no

undue discomfort. On the other hand, in another trial, at an index of 6, a second subject stated that conditions were barely tolerable towards the end of the two-hour period. Physical fitness was an important factor affecting endurance, for it was noted that lack of normal sleep the previous night was sometimes reflected in greater exhaustion on the part of the subject, despite the fact that the effect was not revealed in the index. Allowing for such considerations, and based on the subjects' comments and objective observation, an index of 7 was considered an acceptable upper limit under the conditions of the tests. Reference to Fig. 4 shows that, whereas a "control" would have suffered this degree of discomfort at 92.5° F. effective temperature, the subjects wearing the impervious suits would have

TABLE 3
LIMITING CLIMATIC CONDITIONS FOR A PHYSIOLOGICAL INDEX OF 7 UNDER STANDARD WORKING CONDITIONS

Dry-bulb Temperature	Maximum Wet-bulb Temperature at Various Ventilation Rates		
	5 ft. ³ /min.	15 ft. ³ /min.	Control
°F.	°F.	°F.	°F.
110	70.5	80.5	87.5
100	75	84	90.5
90	80	88	—

FIG. 4.—Physiological index compared with effective temperature at various ventilation rates. $\times$ 5 ft.³/min.; Δ 10 ft.³/min.; $\circ$ 15 ft.³/min.; + Controls.

reached a similar condition at 83.2° F. effective temperature if ventilated at 5 ft.³/min., or at 88.2° F. at 15 ft.³/min. The practical significance of these results can be seen in detail from reference to the effective temperature chart from which Table 3 has been constructed.

Linear interpolation is satisfactory within the range of the table. For practical purposes, in this range every increase of 1° F. in the wet-bulb or 2° F. in the dry-bulb temperature requires about an extra 1 ft.³/min. ventilation to maintain similar conditions of comfort. The figures are shade temperatures and take no account of solar heat load.

Fig. 5 shows effective temperatures in terms of wet- and dry-bulb temperatures. Broken lines are superimposed on the chart to correspond to a physiological index of 7 at various ventilating rates under the working conditions of the experiment. Lines corresponding to other indices can be drawn in with the aid of Fig. 4.

The supply of ventilating air was in no case sufficient to maintain thermal equilibrium nor was the degree of comfort afforded equal to that of the controls. The failure of the ventilation to maintain thermal equilibrium and the progressive discomfort suffered by the subjects was observed by psychrometric measurements of the atmosphere in the enclosed space within the coveralls, which showed a

FIG. 5.—Chart showing effective temperature and limiting atmospheric conditions for a physiological index of 7.

steady rise in humidity punctuated by surges at exercise periods. It rose from a few per cent. above that of the chamber atmosphere and approached saturation during the second hour of the test. In almost all cases the final relative humidity within the suit was between 95 and 100%. The difference between the rectal and enclosed space temperatures ranged from 17° F. under the mildest chamber conditions to 2.4° F. under the most severe. This difference is plotted against the physiological index in Fig. 6, which shows that a difference of approximately 6° F. corresponds to the limiting index 7, referred to above. A subject should, therefore, maintain a satisfactory thermal state and be capable of additional effort regardless of ventilation conditions provided that the difference does not become less than this figure. This criterion promises to be a very useful additional check on the response of subjects during the course of a trial.

Figs. 7, 8, and 9 show the change in rectal temperature, final pulse rate, and total sweat loss respectively, plotted against effective temperature. It will be noted that, although under certain conditions one or other of these factors appears to be a satisfactory index, *e.g.*, pulse rate at high strain, in general they are inferior to the combined index as a measure of strain over the complete range of conditions used in these experiments.

FIG. 6.—Physiological index compared with difference between rectal and suit space temperatures. $\times$ 5 ft. 3 /min.; Δ 10 ft. 3 /min.; $\circ$ 15 ft. 3 /min.

FIG. 7.—Change in rectal temperature compared with effective temperature at various ventilation rates. $\times$ 5 ft. 3 /min.; Δ 10 ft. 3 /min.; $\circ$ 15 ft. 3 /min. + Controls.

FIG. 8.—Final pulse rate compared with effective temperature at various ventilation rates. $\times$ 5 ft. 3 /min.; Δ 10 ft. 3 /min.; $\circ$ 15 ft. 3 /min. + Controls.

FIG. 9.—Total sweat loss (lb.) compared with effective temperature at various ventilation rates. $\times$ 5 ft.³/min.; Δ 10 ft.³/min.; $\circ$ 15 ft.³/min.; + Controls.

Summary

Tests have been conducted using a group of healthy volunteers between 18 and 25 years of age wearing impermeable clothing and performing a standard amount of exercise under controlled conditions of temperature and humidity simulating warm, temperate, hot moist, and hot dry conditions. Lightly clothed controls were used in all tests.

The suits were ventilated with ambient air at rates of 5, 10, and 15 ft.³/min., the air being distributed to six points within the suit. No single physiological measurement was adequate under all conditions, and a composite index of strain was therefore calculated. Under the more rigorous conditions complete equilibrium of temperature could not be maintained. An index of acceptable strain was adopted.

The results relate wet-and-dry bulb temperatures with the minimum ventilating rate required to remain within the acceptable strain index. A chart showing this relationship is included as Appendix 2.

A miniature thermoelectric psychrometer to measure the wet-and-dry bulb temperatures within the suit is described in Appendix 1.

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APPENDIX 1

The Thermo-electric Psychrometer

The main body of the unit (Fig. 10) is constructed from a perspex block A. The horizontal drilling, B, which serves as the aspiration channel, extends through a small tubular section, C, at one side of the perspex block, to enable attachment of the unit to the source of suction. Two vertical drillings, D and E, connected with the aspiration channel, accommodate the leads to the wet and dry junction. The larger drilling, D, serves also as a water reservoir.

The thermocouple wires are 28 gauge constantan and 36 gauge copper. The wet junction wires are threaded through the rubber stopper, F, soldered, varnished, and wound with a single layer of loosely spun cotton. The junction is located in the aspiration channel with the ends of the thread "wick" dipping into the reservoir which is

FIG. 10.—Construction of the thermo-electric psychrometer.

FIG. 11.—Nomogram combining the curves of Fig. 4 (scales labelled at top) with those of Fig. 5 (scales labelled at the bottom) (see Appendix 2).

filled by inserting a suitably bent pipette through the channel at C. The dry junction is soldered and threaded through the drilling E. Air is drawn through the channel at a rate of not less than 20 ml./min. An 8 in. $\times$ 1½ in. Dewar flask for the cold junction completes the unit.

APPENDIX 2

Nomogram

Fig. 11 is a nomogram which combines the curves of

Fig. 4, represented by the scales labelled at the top, and those of Fig. 5 by the scales labelled at the bottom. The effective temperature scale is common to both portions of the nomogram. The broken lines A and B illustrate a typical application of the nomogram: A shows that a dry-bulb temperature of 101°F. and a wet-bulb temperature of 80°F. represent an effective temperature of 86°F., and B shows that under these conditions a ventilation rate of 10 ft.³/min. is required if the physiological index is limited to 7.