PRACTICAL EVALUATION OF SOLAR HEAT LOAD ON HUMAN BODY

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ABSTRACT

The practical difficulties in computing the solar heat load from basic data using Blum's equations, have been discussed. Limitations of several instruments designed from time to time for measuring the separate components of solar heat load or for integrating them into a composite index have also been pointed out. An attempt has been made in this paper to show on theoretical grounds, that for practical purposes, most of the difficulties can be avoided by retaining the use of the popular black globe thermometer, and providing a correction to its reading for the particular colour of clothing or complexion of skin, for clothed or nude subject in the erect posture. The validity of the conclusion has been judged against available data.

Introduction

Solar heat load or stress on the human body is, according to Blum[1], that portion of the total heat load, which is due to sun-light, both direct and reflected. This definition ignores the long infra-red radiation exchange between the human body and the terrain which is heated by solar radiation. Assessment of solar heat load on clothed or nude human body is a problem of considerable importance both in civil and military life, especially in tropics.

The highly complicated nature of the problem was clearly brought out in the admirable analysis of Blum[1], who expressed the total solar heat load as the sum of the loads received directly from the sun and indirectly from the sky and the terrain. Mani and Mehra[2] attempted to compute the solar heat load R, by making use of Blum's results and incorporating the degree of cloudiness of the sky, as introduced by Burton[3]. They put the equation in the form

$$R = 1158\, t^{Sec\, Z} (1 - 0{\cdot}9x)\ (1 - F)\ mCals/m^2/hr \qquad (1)$$

in which 1158 is the solar constant, t the transmission factor of the atmosphere, Z the zenith distance of the sun depending on the solar declination, latitude of the place and the hour-angle, x the degree of cloudiness, F the reflectance of the skin or clothing for solar radiation and m is a trignometrical function of Z given by

$$m = 0{\cdot}30\,(Cos\, Z + Sin\, Z) \text{ for erect posture} \qquad (2)$$

$$\text{and } m = 0{\cdot}45\, Cos\, Z + 0{\cdot}07\, Sin\, Z \text{ for prone posture} \qquad (3)$$

The equation of solar heat stress is evidently one of theoretical interest only, because of the highly variable and uncertain factors required for its computation. Further, the albedo of the terrain which has been assumed[1] to be 0·25 on the average, varies considerably with the optical characteristics of the terrain.

One way of avoiding the uncertain factors in equation (1) is to find S, the intensity of direct solar radiation on a plane normal to the rays, from measurements with a pyrheliometer, *e.g.*, of the Eppley type, where

$$S = 1158\, t^{Sec\, Z}\, (1 - 0{\cdot}9x)\ Cals/m^2/hr \qquad \ldots \quad \ldots \quad \ldots \quad (4)$$

So that equation (1) reduces to

$$R = S\,(1 - F)m\ Cals/m^2/hr \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

Even this equation is affected by the variability of the albedo or reflection coefficient of the terrain.

The Pan-radiometer developed by Richards, Stoll and Hardy[4] has been claimed to be an absolute measuring instrument for environmental radiation. Apart from the elaborateness of the apparatus and its method of use, the result is predominantly influenced by the differences in the emissivities of the various spheres employed so that an accurate knowledge and stability of their optical characteristics are essential for the accuracy of the results.

For separate assessment of the mean radiant temperatures of the sky and the terrain, excluding both direct and indirect solar radiation (*i.e.*, visible and short infra-red), a thermal radiometer was developed by Stoll and Hardy[5]. It is not an integrating type like the Pan radiometer, and has to be pointed at different directions to the sky and the terrain, and the readings averaged.

It will be clear from the foregoing that these instruments cannot be of much practical use as field instruments. Moreover, their readings are not directly interpretable in terms of solar heat load on man, because different parts of his body are differently exposed to the sky and terrain, although Hardy and Stoll[6] have assumed that the scattered and reflected radiation come from practically all directions. This assumption is not justified, as was pointed out by Blum[1] much earlier. A horizontal surface facing up is exposed to the entire sky, while a vertical surface is exposed to half the sky. Another difficulty is that the instrument readings do not take into account the different emissivities of clothing or skin for solar radiation, although Hardy and Stoll[6] included this effect in a rough way by assuming an average value of 0·5 for the emissivity of a clothed man, which, according to them can be anything between 0·2 for white clothing and 0·95 for black clothing.

The considerations out-lined above, naturally led us to explore the possibility of using the popular black globe thermometer of Vernon[7]. The objections against the use of the black globe for the assessment of solar heat load, are, as stated by Mani and Mehra[2], *firstly*, that the black globe does not take into account the effect of posture of the human body in relation to the sun, sky, and terrain, and *secondly*, that it does not take into account the effect of the colour of clothing or complexion of skin. The first objection is valid on account of the spherical shape of the globe, and was pointed out by earlier workers, *e.g.*, Bedford and Warner[8].

The object of the present study is to show on theoretical grounds, how, by overcoming these two objections, the black globe can be usefully employed as a simple field instrument for the assessment of solar heat load on man, to point out its limitations, and to test the validity of the method against available data on simultaneous observations on the black globe and pyrheliometer.

Radiation Increment to Dry-bulb Temperature

The problem of assessment of thermal stress has been solved in a fairly satisfactory way under indoor conditions with surrounding surfaces at the same temperatures as the ambient air. The factors contributing to the thermal stress, namely air temperature, air movement and humidity, are easily measureable and can be integrated into a composite index of environmental warmth. In this connection, the effective Temperature (E.T.) scale of comfort developed by Houghten, Yaglou and Miller [9, 10, 11] is the most popular and useful index, and deserves special mention. In the presence of additional radiation from hot surfaces, our task will be greatly simplified if we can express the radiant heat load as a correction to be applied to the dry bulb temperature, so as to reduce the given environment into a thermally equivalent indoor environment with the walls and the air at the corrected temperature. This was achieved by Burton[3] in a simple way. He expressed the thermal radiation increment to the environmental 'shade temperature', by the formal RI_a/C, where R is the radiant heat load in Cals/m²/hr, I_a the air-insulation in 'Clo' units, depending on the air movement, and C is the conversion factor, being 3·09 for Fahrenheit scale and 5·55 for Centigrade scale. Thus if T_a be the prevailing air temperature, and T'_a, the air temperature corrected for solar radiation, and R, the solar heat load as given by equation (5), then we have,

$$T'_a - T_a = \frac{RI_a}{C} = S(1 - F)m \,.\, \frac{I_a}{C} \qquad \ldots \qquad \ldots \qquad (6)$$

where S, the intensity of direct solar radiation, can be read directly from a pyrheliometer, as mentioned earlier. Mani and Mehra[2] expressed the solar heat load calculated from pyrheliometer readings, as a 'Solar radiation increment to dry bulb reading' as given by equation (6), although, unfortunately, they did not measure the air velocity for determining I_a, the air insulation, but assumed an average value of 300 ft/min, while outdoor air movement is subject to considerable fluctuations.

Black Globe in the estimation of solar heat load on human body

It is proposed to present a simplified analysis of the problem on the basis of a few assumptions, the validity of which for practical purposes, has been more or less established by earlier workers. The black globe has been assumed to be a thin sphere of copper, 6″ in diameter, painted dull black, as described by Bedford and Warner[8]. The assumptions made are as follows :—

(*i*) The emissivity of the black globe is practically the same for visible, short and long-infra-red radiation, and is taken to be [4, 8] 0·95.

(*ii*) The emissivities of the black globe, human skin of all complexions and clothing of all colours, are very nearly the same for indoor radiation which is exclusively long-infra-red[13].

(*iii*) Convective heat exchange per unit area for the human body is practically the same as that for a six-inch sphere[14].

The first thing to be considered is the effect of posture on the solar heat load and the consequent limitations of the black globe. There after, it will be attempted to find a correction to air temperature for the effect of solar radiation in terms of the black globe thermometer reading.

(*a*) *Solar heat load in relation to posture*

A close inspection of equations (2) and (3) shows that while thefactor 'm' varies considerably with Z for the prone posture, it is reasonably steady for the erect posture. In fact, for the most part of the day, with Z lying in the range 20° to 70°, the factor (Sin Z + Cos Z) lies in the range 1·28 to 1·41. Consequently, there is no reason why the black globe should not be applicable to the erect posture, since by virtue of its spherical shape it is unable to take into account the position of any localised source of radiation, such as the sun. The erect posture, as we know, is the common posture for most of our outdoor activities, *e.g.*, marching with load, ploughing in the field, and so on. It should be noted, however, that the intensities of the total solar radiations incident on the human body in the erect posture and the black globe are not likely to be the same but should in general differ by a constant factor the value of which may not be much different from unity.

(*b*) *Solar radiation correction to air temperature in terms of black-globe thermometer reading*

We consider an erect human body, clothed or nude, exposed to a given outdoor environment in the sun, where the shade temperature and air velocity are T_a and V respectively. It is our object to find a thermally equivalent indoor environment with the same air velocity, but having the surrounding surfaces and the air at some common temperature T'_a, such that the total radiant and convective heat load on the body remains the same in both the environments. In that case T'_a may be regarded as the air temperature corrected for solar radiation, which, for the present purpose, is taken to be the radiant heat load in excess of what would have been encountered in the absence of any source or sink of radiation, the surrounding surfaces being at the air temperature T_a.

If T_s be the mean surface temperature of the human body, clothed or unclothed, Q the total solar radiation, direct and indirect, incident on the body per unit area, and F the reflectance of the skin or clothing for solar radiation, then the total radiant and convective heat load H_{RC} on the body per unit area, will be given by

$$H_{RC}=[0\cdot95\sigma f_R\,(T^4_a - T^4_s) + bf_c\,\sqrt{v}\,(T_a - T_s)]+(1-F)f_R\,Q \qquad (7)$$

where σ is stefan's constant and b, the convection constant, T_a and T_s being expressed in the aboslute scale. Here f_R and f_c are the fractions of the Dubois area effective in radiation and convection exchange. Conduction in such cases plays an insignificant role.

In a thermally equivalent indoor environment at the uniform temperature T'_a, as defined earlier, H_{RC} will remain unchanged, so that

$$H_{RC} = 0 \cdot 95\sigma f_R (T'^4_a - T^4_s) + bf_c \sqrt{v} (T'_a - T_s) \quad .. \quad (8)$$

From equations (7) and (8) we have

$$0 \cdot 95\sigma f_R (T'^4_a - T^4_a) + bf_c \sqrt{v} (T'_a - T_a) = (1 - F) f_R Q \quad .. \quad (9)$$

Let us now consider a 6″ black globe thermometer in thermal equilibrium with the given out-door environment. If T_g be its steady reading, then for thermal balance, we have for practical purposes,

$$0 \cdot 95\sigma(T^4_g - T^4_a) + b\sqrt{v}(T_g - T_a) = 0.95 Q_g \quad .. \quad (10)$$

where Q_g is the total solar radiation incident on the globe per unit area.

Equations (9) and (10) may be approximated by

$$(4 \times 0 \cdot 95\sigma f_R T^3_{aa'} + bf_c \sqrt{v})(T'_a - T_a) = (1 - F) f_R Q \quad .. \quad (11)$$

and, $$(4 \times 0 \cdot 95\sigma T^3_{ag} + b\sqrt{v})(T_g - T_a) = 0 \cdot 95 Q_g \quad .. \quad .. \quad (12)$$

where T_{aa}' is the mean of T_a and T'_a and T_{ag} is the mean of T_a and T_g, expressed in the absolute scale.

For most practical situations, T_{aa}' and T_{ag} will not differ appreciably. Moreover, f_R and f_C for the erect human body are not materially different and may be taken to be [14] 0·75 for the present purpose. With these approximations, equations (11) and (12) lead to

$$T'_a - T_a = \frac{1 - F}{0 \cdot 95} \cdot \frac{Q}{Q_g} \cdot (T_g - T_a) \quad .. \quad .. \quad (13)$$

The ratio Q/Q_g, as explained earlier, is practically constant, and should be nearly equal to unity. Thus $(T'_a - T_a)$, as given by equation (13), is the required correction to air temperature for solar radiation. The environmental heat load (Radiant plus convective) can then be evaluated from equation (8), which may be rewritten in the form,

$$H_{RC} = (4 \times 0 \cdot 95\sigma T^3_{sa'} + b\sqrt{v}) \cdot 0 \cdot 75(T'_a - T_s) \quad .. \quad (14)$$

Where $T_{sa'}$ is the mean of T_s and T'_a expressed in the absolute scale.

The above treatment, although over simplifying a rather complicated problem, nevertheless, serves to stress the importance of retaining the use of the black globe thermometer, as an extremely simple and practical instrument for the estimation of solar heat stress on the erect human body, clothed or nude. Some of the chief advantages of the black globe thermometer over the pyrheliometer in the assessment of solar radiation correction to air temperature are, (*i*) it does not require the knowledge of zenith distance and air movement, as will be evident from equations (6) and (13); (*ii*) it is independent of the uncertain factors like scattering coefficient of the sky and reflection coefficient of the terrain. The usual forms of pyreheliometer, as for example, the Eppley type, measure the intensity of direct solar radiation on a horizontal plane, which multiplied by Sec Z will give the value of S, the intensity of direct solar radiation on a plane normal to the rays.

Black Globe under indoor conditions

Under indoor conditions, we can reasonably take $(1 - F) \doteq 0 \cdot 95$, for all complexions of skin or all colours of clothing. Moreover, in the absence of any localised source of radiation, Q will be equal to Q_g in equation (13), whence it immediately follows that

$$T'_a = T_g \qquad \ldots \quad (15)$$

so that the black globe reading itself may be taken as the air temperature corrected for radiation. This appears to provide a theoretical justification for the arbitrary radiation correction to the dry bulb reading as proposed by Vernon and Warner[15]. They also proposed a corresponding correction to wet bulb reading, which does not see n to be justified on theoretical grounds[16]. In the Corrected Effective Temperature (C.E.T.) scale proposed by Bedford[17] the dry bulb reading in the Effective Temperature (E.T.) chart is replaced by the black globe reading, when T_g and T_a differ appreciably, but no corresponding correction to wet bulb reading is applied, which can be done in a simple manner with the help of a nomogram[18]. The use of the black globe will, however, not be justified if localised sources of radiation are present in the room[8].

Validation of the theory against available data

Simultaneous observations on the pyrheliometer and the black globe thermometer in the sun, were taken by Mani and Mehra[2], which can therefore be utilised for testing the validity of the foregoing analysis, at least in a rough way. In Tables 1 and 2, the dry bulb and black globe temperatures are shown in columns 1 and 2 respectively. They have not presented the pyrheliometer readings, but given the solar radiation increment to dry bulb as estimated from pyrheliometer reading according to equation (6), for 3 different colours of clothing (Table 1) and 3 different shades of skin (Table 2).

TABLE 1 (CLOTHED SUBJECTS)

Comparison of Mani & Mehra's values with those of present authors, for Solar Radiation correction to Dry Bulb reading for different colours of clothing

Temp. in Shade °F Dry Bulb	Black Globe Temp. In Sun °F	Solar Radiation Correction to Dry Bulb Reading °F					
		White clothing (1—F) = 0·25		Olive green clothing (1—F) = 0·57		Black clothing (1—F) = 0·86	
		Mani & Mehra	Present authors	Mani & Mehra	Present authors	Mani & Mehra	Present authors
1	2	3	4	5	6	7	8
105·0	128·5	7·1	6·5	16·2	14·4	24·4	21·9
104·0	129·0	7·1	6·8	16·2	15·4	24·4	23·3
102·0	127·0	7·3	6·8	16·7	15·4	25·2	23·3
105·0	129·5	7·2	6·7	16·4	15·0	24·7	22·9
103·0	131·0	7·2	7·6	16·5	17·1	24·9	26·1
103·0	129·5	6·9	7·2	15·7	16·2	23·7	24·7
105·0	132·5	7·1	7·5	16·2	16·8	24·4	25·6
106·5	135·0	7·3	7·6	16·6	17·4	25·0	26·5
100·0	122·2	6·9	5·9	15·7	13·6	23·7	20·7
100·0	130·2	6·9	8·2	15·7	18·5	23·7	28·2
106·0	133·7	6·2	7·6	14·2	17·0	21·4	25·8
107·0	131·5	6·8	6·7	15·5	15·0	23·4	22·9
103·0	130·5	6·0	7·5	13·8	16·8	20·8	25·6
104·0	128·0	6·6	6·5	15·0	14·7	22·6	22·3
105·0	133·0	7·1	7·6	16·2	17·1	24·4	26·1

TABLE 2 (NUDE SUBJECTS)

Comparison of Mani & Mehra's values with those of present Authors for Solar Radiation correction to Dry Bulb reading for different shares of skin

Temp. in Shade °F Dry Bulb	Black Globe Temp. in Sun °F	Solar Radiation Correction to Dry Bulb Reading °F					
		Negro Skin (1—F) = 0·84		Brunette Skin (1—F) = 0·65		Blonde Skin (1—F) = 0·57	
		Mani & Mehra	Present authors	Mani & Mehra	Present authors	Mani & Mehra	Present authors
1	2	3	4	5	6	7	8
102·0	127·0	24·6	22·6	19·0	17·4	16·7	15·4
105·0	128·5	23·9	21·2	18·5	16·4	16·2	14·4
100·0	122·2	23·1	20·0	17·9	15·6	15·7	13·6
107·0	131·5	22·8	22·1	17·6	17·1	15·5	15·0
105·0	133·0	23·9	25·2	18·5	19·6	16·2	17·1

The reflectance values for white, olivegreen and black clothing, as used by them, are 0·75, 0·43 and 0·14 respectively for solar radiation. The values for Negro, Brunette and Blonde skin are taken to be 0·16, 0·35 and 0·43 respectively. These values ignore the long infra-red component of the total radiation exchange. The solar radiation correction to dry bulb reading as estimated by them for different clothings and skins are shown in columns 3, 5, 7 in Tables 1 and 2. The accuracy of their estimated corrections is undoubtedly affected by their assumed constant air movement of 300 ft./min, as mentioned earlier.

From the black globe and dry bulb readings, using the same reflectance values as used by Mani and Mehra, we estimated the values of the expression

$$\frac{1-F}{0\cdot 95}\,(T_g - T_a)$$

for all the above cases. The values so obtained were found, on the average, to be 2·5 per cent below the values of Mani and Mehra. It follows therefore, from equation (13) as developed in this paper, that the constant ratio Q/Q_g has an average value of 1·025. With this value we have calculated the solar radiation corrections which have been shown in columns 4, 6, 8 in Tables 1 and 2.

To test statistically the significance of difference between the two sets of paired data, analysis was performed on the logarithms of the of estimates, because the difference should be judged in relation to the size of the estimate. For the present purpose, all the data were pooled regardless of clothing and skin. The value of '*t*' works out to be 0·00279 for frequency 58, indicating that the difference between the two estimates of solar radiation correction is not at all significant ($P > 0\cdot 90$). The values obtained from black globe readings have been plotted in Fig. 1, against those computed by Mani and Mehra from pyrheliometer readings, on logarithmic scales. The scatter may be largely due to the

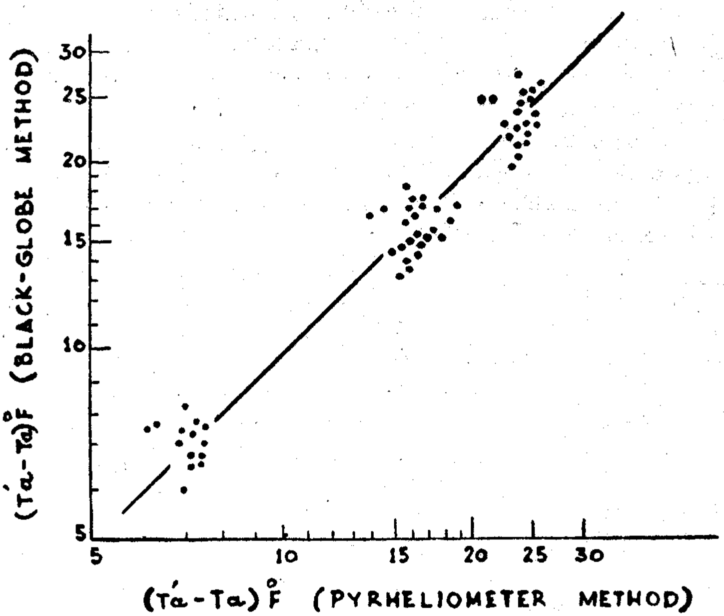

FIG. 1—Comparison between black-globe method and Pyrheliometer method of estimation of Solar-Radiation correction to Dry-Bulb temperature.

fluctuations of the prevailing outdoor air movement on either side of 300 ft./min., the value assumed by Mani and Mehra.

In view of the complexity of the problem, and the simplifying assumptions made in the theory outlined in this paper, the agreement between the two independent estimates seems to be rather extraordinary. This may be due to several factors opposed to one another. Mani and Mehra's estimate ignores the long infra-red radiation exchange between the human body and the sky and the terrain. The black globe on the other hand, responds equally to all the radiations incident on it, but to enable comparison with Mani and Mehra's estimates, we have used the same reflectance values as used by them, which are valid only for visible and short infra-red radiations. Fluctuations of air movement will affect Mani and Mehra's estimates but not those based on black globe, its temperature being directly influenced by the prevailing air movement. The above considerations show that the available data cannot be fully relied upon for establishing the validity of the theory, but they do emphasise the need for exploring further, the possibilities of the black globe thermometer as a simple and practical field instrument for assessment of solar heat load on the human body in the erect posture. For this purpose, it will be necessary to take accurate and simultaneous observations on black globe, pyrheliometer and air movement, during different times of the day, and under different sky conditions.

Conclusions

It will be seen from the foregoing that computation of solar heat load on the human body from the basic data on zenith distance of the sun, latitude and altitude of the place, time of the year and day, and the degree of dustiness or cloudiness of the atmosphere, is hardly of any practical value, not only because of the complicated procedure, but also due to the multitude of uncertain factors, notable among them being the degree of cloudiness, scattering coefficient of the sky, reflection coefficient of the terrain, and the state of dryness or wetness of the atmosphere throughout the path of the direct rays.

More reliable results can be obtained from pyrheliometer readings, in conjunction with the zenith distance of the sun, but even then the uncertain factors are not all eliminated, particularly the scattering coefficient of the sky and reflection coefficient of the terrain.

The Pan radiometer of Richards[4] *et al* and the Thermal radiometer of stoll and Hardy[5], though suitable for certain types of radiation measurements, cannot be conveniently used for predicting solar heat load on man. These instruments and their methods of use are rather elaborate, and are not likely to be of much use as field instruments. Moreover, their readings are not directly interpretable in terms of solar heat load on man.

For practical purposes, it has been shown in this paper, that most of the difficulties can be overcome, at least for the erect posture, by retaining the use of the popular black globe thermometer of Vernon[7], which is also an integrating type. From its reading, together with air temperature and the reflectance of clothing or skin, the solar heat load can be readily expressed as an increment in the dry bulb or shade temperature, for which purpose air velocity need not be known. Except for the fact, that the globe cannot be used for all postures, it is the simplest instrument and has proved to be of great value in field work. Moreover, the erect posture, for which the black globe can be used, is the common posture for most of our outdoor activities.

In the present paper, long-infra-red radiation exchange between the human body and its surroundings has been ignored. It can also be included by modifying the reflectance values of clothing and skin for the combined effect of the total radiation. We have found [19] that the black globe can also be used for simple assessment of such reflectance values, which are obviously higher than the values for direct solar radiation.

The air temperature, corrected for radiation in the manner indicated, has been used by us in the place of dry bulb temperature in the Effective Temperature (E.T.) chart, with corresponding correction applied to the wet bulb readings, and the resulting index has been named as the Modified Effective Temperature[18] (M.E.T.), as a measure of total environmental warmth including solar heat load.

The wet bulb globe temperature index (W.B.G.T.) recently developed in the U.S.A., combines the wet bulb, black globe and the dry bulb temperatures into a composite index and is supposed to be a measure of environmental warmth in the sun as well, although it does not require a knowledge of the pervailing air movement nor does it take into account the different colours of clothing and different complexions of skin. However, detailed information on this index is lacking. Nevertheless, it is quite evident that the black globe is getting better recognition which it fully deserves.

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References

1. Blum, H.F., *J. Clin. Inrest.*, **24**, 712, 1945.
2. Mani, K. V. and Mehra, N.C., *J. Sci. Industr. Res.*, **16c**, 61, 1957.
3. Burton, A.C., (Assessment of Thermal Demands of The Environment) (Paper presented by Canada at the 4th Commonwealth Conference on clothing and General Stores), 1953.
4. Richards, C. H., Stoll, A. M. and Hardy, J. D., *Rev. Scient. Instruments*, **22**, 925, 1951.
5. Stoll, A. M. and Hardy, J. D., *J. Appl. Physiol.*, **5**, 117, 1952.
6. Hardy, J. D. and Stoll, A. M., *J. Appl. Physiol.*, **7**, 200, 1954.
7. Vernon, H. M., *J. Ind. Hyg.*, **14**, 95, 1932.
8. Bedford, T. and Warmer, C. G., *J. Hyg.*, **34**, 463, 1934.
9. Houghten, F. C., Yaglou, C.P., *Trans. Amer. Soc. Heat. and Ventil. Engrs.*, **29**, 163, 1923.
10. Houghten, F.C., and Yaglou, C.P., *Ibid*, **30**, 193, 1924.
11. Yaglou, C.P. and Miller, W.E., *Ibid*, **31**, 89, 1925.
12. Majumdar, N.C., *I.J. Physiol., and Allied Sciences*, **7**, 205, 1953.
13. Fourt, L. and Harris, M. *Physiology of Heat Regulation and Science of Clothing*, Newburg, L.H. (W.B. Saunders Co., Philladelphia), 291, 1949.
14. Hardy, J.D., *Physiology of Heat Regulation and Science of Clothing*, Newburg, L.H. (W.B. Saunders Co., Philadelphia), 78, 1949.
15. Vernon, H.M. and Warner, C.G., *J. Hyg.*, **32**, 436, 1932.
16. Majumdar, N.C.—paper to be published.
17. Bedford, T., Environmental Warmth and its Measurement, Medical Research Council War Memorandum No. 17 (H.M.S.O., London), 24, 1946.
18. Majumdar, N.C., *Def. Sci. J.*, Section B, **8**, 248, 1958.
19. Sharma, R.N. and Majumdar, N.C.—paper to be published.