a preceding one [6], to serve several reasonable interests of the Committee on Biotechnology of the Heat Transfer Division.

(*a*) One of these aims has been achieved by condensing calorimetric data on seated, clothed human subjects into linear differential equations which permit the bio-engineer to quickly approximate the effect of complex air and radiant temperatures on the human element of a man-machine design problem.

(*b*) These aims have been accomplished for a range of thermal loads typical of the region from 40 to 80 F, and separately by reason of different human temperature regulation characteristics, for the range from 80 to 105 F.

(*c*) Static heat exchangers—an electrically heated model of the human body and a hemispherically capped cylinder—have been used to establish an experimental connection between the heat-exchange properties of these inanimate bodies and linear differential equations which generalize the thermal interchanges of the human body as observed in a calorimeter environment.

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DISCUSSION

E. F. Adolph[2]

The author reduces the results of certain measurements of heat exchanges by clothed men to linear equations. These equations are based on the concept that the physical components of exchange—radiation, conduction, convection, and evaporation—as well as metabolic heat production, combine to influence the mean surface temperature of the human body. Radiative or wall temperatures were varied independently of the convective or air temperatures, to provide a wide range of atmospheric conditions for men from whom the necessary data were obtained. A previous paper of the author covered the range of "operative" environmental temperatures from 40 to 80 F; the range 80 to 105 F is now included by a similar linear equation which, however, has different coefficients for each of the five terms. In this range the physiological regulation of body surface temperature differs greatly, since evaporative cooling now predominates.

It is very satisfying to have an empirical equation that condenses into it the varieties of information needed for assessing the steady state of heat regulation achieved by resting clothed individuals. The author's contribution consists chiefly in the use of surface temperature as the parameter most readily related to the physical conditions of environment. By this means, his two equations, of similar dimensions, become available to describe the net physiological state in any environment within the wide range indicated.

I agree with the author that this method of presenting calorimetric data advances the physical description of heat exchanges of the human body. It would be interesting to compare the accuracies of prediction of physiological effects, first from these two equations, and then from charts for effective temperatures and for other empirical relations that have been in use.

I also like the author's partial evaluation of the differences in heat exchange between the "copper man" as a model system and the average human subject. Differences between model and subject will allow us to identify special characteristics of heat regulation in man.

Alan H. Woodcock[3]

This paper, extending an earlier one by the same author, will be welcomed both by engineers and others who must consider the thermal relationships between man and his environment. The author and his co-workers have accumulated great quantities of pertinent information. However, to those not thoroughly familiar with this field, such masses of data are often baffling. His reduction or condensation of it into the form of simple linear equations, which can be easily used, is indeed a real service and, needless to say, must be performed by one thoroughly familiar with it.

The results with the life-sized model of man in this paper are reassuring as they indicate that man obeys the physical laws of heat transfer in a manner similar to an inanimate object. Table 1 indicates that the equation derived from human data gives good agreement with the model at an air temperature of 68.7 F. However, over the relatively small range (15 deg) of calorimeter temperature, the difference in skin temperature between equation and model shows a rather poor correlation. For the model with fixed heat input, the term in equation (1) representing metabolic heat input is constant and that for evaporation is also considered as a constant. Reference to Table 3 shows that neither metabolism nor evaporation remain constant for man as ambient temperature varies. If it did, these terms would have been omitted. Had the author used a variable heat to his model to correspond with man's variable metabolic heat production at varying temperatures and also corrected his evaporative term to correspond with temperature, I am sure he would have obtained a closer agreement between model and equation at all temperatures. Such corrections are, however, complications which are not necessary if, as the author recommends, the correct ambient temperature is used.

His introduction of a much simplified model in the form of a cylinder with hemispherical ends has both advantages and disadvantages. Its advantages are the reduced size and simplification of shape which, of course, reduces cost and at the same time makes an instrument much easier to store and use. Its disadvantage is that the effects of different types of clothing cannot be compared on the cylinder since it is impossible to duplicate the fit and drape of clothing. However, such complications are really beyond the scope of the author's objective which is to rid

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the problem of its complications and present the data in its original form. An instrument somewhat similar to this cylinder, which is used in a slightly different manner, is the globe thermometer of Vernon. This globe thermometer, which is a six-inch diameter hollow-blackened copper sphere with a thermometer inserted in it, has been used with considerable success to integrate the effects of air and radiant temperature and is rapidly gaining popularity in this country.

In a later section of his paper, the author proposes a new equation [his equation (10)] to extend the range up to 105 F. A comparison of equations (1) and (10) shows that all the numerical coefficients in equation (10) except the constant term have been reduced. This indicates that at higher temperatures variation of skin temperature decreases. Indeed, skin temperatures become a relatively poor index of heat stress on man since they are so insensitive.

The effect of humidity is also not included in equation (10) although it is well known that it is an important factor. However, he indicates that his work will be extended to include these factors. Such an extension is definitely required and it is hoped that he will complete it in the near future.

Author's Closure

Dr. Woodcock comments on an interesting feature of equation (1) for the 40 to 80-deg F range as compared with equation (10) for the 80 to 105-deg F range. He notes that the coefficients of equation (10) for the hot region are reduced with respect to equation (1) for the cool region. This fact is interpreted as an indication of a smaller skin temperature variability at higher ambient temperatures, and possibly as a restriction on the use of skin temperature as an index of heat stress in the hot region. It is true that the rate of change of skin temperature is slower as ambient stress increases. However, where the measurement panel contains the evaporative value whose systematic increment (of opposed sign) maintains this slower skin rise, there is no change in the total amount of information incorporated by empirical multiple variable equations of equally good fit in the two regions. In general, one cannot compare the absolute coefficient values of such equations as (1) and (10) without expressing them in beta form, see equation (3).

Likewise, the equations do not contain a thesis as to which variable is the best index of heat stress. From the value of the multiple correlation coefficient for equation (10) the total information extracted from the hot-series data is of the same order as that incorporated in the cool-region analysis equation.

These equations are numerical devices for expressing condensed interrelations as measured. Since they have simple algebraic properties, the total evaporation (E) could be made the dependent variable, if we regard this as the best thermal stress measure. In bio-engineering application within the range of the equation and its individual variables, the data interrelations will remain constant for this body of calorimetric data, analyzed by the methods described, without regard to which variable is regarded as the predicted variable.

An analysis in process will include a vapor pressure term. For documentation of equation (10) which is briefly mentioned in the text, and equation (1) it may be added that relative humidities were held between 40 and 50 per cent for every experimental air temperature.