

"predicted 4-hour sweat rate" (P4SR) can be obtained for any environment combination of air, mean radiant and wet-bulb temperatures and air velocity, and for different levels of work. From this chart one can determine the acceptability of a hot environment or the degree of improvement necessary to secure a predicted sweat rate within the acceptable limit.

E. CALCULATED LIMITS OF HEAT EXPOSURE TO MAINTAIN THERMAL BALANCE

From the development of the concept of "partitioned calorimetry" at the John B. Pierce Laboratory of Hygiene,⁷ Gagge, Herrington, and Winslow⁸ defined the upper limit of tolerable heat exposure as any maximum thermal environment in which body heat balance is just maintained (for a given work rate) without significant rise in skin temperature. Using the simple heat balance equation:

$$M \pm R \pm C = E$$

where M is metabolic rate, R the radiant heat exchange, C the convective heat exchange, and E the heat loss by evaporation, Haines and Hatch⁹ outlined a physical method for evaluating the magnitude of heat stress imposed on employees in the hot industries. This procedure, which makes use of the coefficients of heat exchange by radiation, convection, and evaporation obtained on nude men at the Armed Medical Research Laboratory,¹⁰ may also be used in determining the most effective control measures and the extent of controls required to bring environmental conditions within the limits necessary to maintain heat balance (with skin temperature 95° F.). For a man of average size the approximate heat balance equations are:

$$E_{\text{required}} = M + 22 (t_w - 95) + 2\sqrt{V} (t_a - 95)$$

$$\text{and } E_{\text{maximum}} = (10.3V)^{0.4} (42 - VP_a)$$

E_{required} is the necessary evaporative cooling rate to maintain balance; E_{maximum} is the maximum evaporative cooling rate for man when the body is fully wetted. The other symbols are: t_w = mean radiant temperature of the surrounding walls in ° F.; t_a = air temperature in ° F.; V = air velocity in f.p.m.; VP_a = vapor pressure of the water vapor in the air in mm. Hg. The values 22, $2\sqrt{V}$, and $10.3V^{0.4}$ are the coefficients of heat transfer for radiation, convection, and evaporation, respectively, each multiplied by the effective surface area of the body. The vapor pressure of water at the skin temperature of 95° F. is 42 mm.

⁷ C.-E. A. Winslow and L. P. Herrington, *Temperature and Human Life*. Princeton University Press, Princeton, N. J., 1949.

⁸ A. P. Gagge, L. P. Herrington, and C.-E. A. Winslow, Thermal interchanges between the human body and its atmospheric environment, *Am. J. Hyg.*, **26**, 84 (1937).

⁹ G. F. Haines and T. F. Hatch, Industrial heat exposures, evaluation and control, *Heating and Ventilating*, **49**, 93-104 (November, 1952).

¹⁰ N. Nelson, L. W. Eichna, S. M. Horvath, and T. F. Hatch, Thermal exchanges of man at high environmental temperatures, *Am. J. Physiol.*, **151**, 626 (1947).

The external heat load, $R + C$, may be calculated from the difference between the "operative" temperature⁷ and the skin temperature:

$$R + C = K_0 (t_0 - 95)$$

where

$$K_0 = 22 + 2\sqrt{V}$$

and

$$t_0 = \frac{22t_w + 2\sqrt{V} t_a}{22 + 2\sqrt{V}}$$

The Vernon globe temperature, t_g ,¹¹ may be used in place of the calculated operative temperature. For any given combination of globe temperature, wet-bulb temperature, air velocity, and work rate, one may quickly determine the ratio, $E_{\text{req.}}/E_{\text{max.}}$ with the aid of the charts in Figure 3. Values of M for different work situations are given in Table 1. The thermal balance line for t_s (skin temperature)

TABLE 1
Estimates of Energy Metabolism for Various Types of Activity
(Values apply for a 154-pound man, and do not include rest pauses)

Activity	B.t.u./hr.
Sleeping	250
Sitting quietly	400
Light work	
Sitting, moderate arm and trunk movements (e.g., desk work, typing)	450-550
Sitting, moderate arm and leg movements (e.g., playing organ, driving car in traffic)	550-650
Standing, light work at machine or bench, mostly arms	550-650
Moderate work	
Sitting, heavy arm and leg movements	650-800
Standing, light work at machine or bench, some walking about	650-750
Standing, moderate work at machine or bench, some walking about	750-1000
Walking about, with moderate lifting or pushing	1000-1400
Heavy work	
Intermittent heavy lifting, pushing or pulling (e.g., pick and shovel work)	1500-2000
Hardest sustained work	2000-2400

95° F., $M = 1100$ B.t.u./hr., and $V = 400$ f.p.m., calculated on the basis of the above coefficients of heat transfer, is compared with Eichna's lines of maximum physiological tolerance in Figure 2.

F. PHYSICAL BASIS OF TOLERANCE LINES

Man's response to heat is complex, and relationships between magnitude of stress and physiological disturbance induced by the heat involve more than simple heat balance. Implicit in the establishment of tolerance limits, however, is the

¹¹ H. M. Vernon, The radiation experienced in factories and houses, *J. Ind. Hyg. Toxicol.*, **19**, 498 (1937).