$$t_o = 0.81\,t_w + 0.135\,[\sqrt{V}\,t_A - (\sqrt{V} - 1.40)\,t_s],$$

*where*

$t_o$ = operative temperature, Fahrenheit degrees.
$t_w$ = mean radiant temperature, Fahrenheit degrees.
$t_A$ = air temperature, Fahrenheit degrees.
$t_s$ = mean skin temperature, Fahrenheit degrees.
$V$ = air velocity in feet per minute.

Under comfortable still air conditions during the heating season, the mean skin temperature of persons normally clothed is between 90 and 93 F (with lower values for the extremities), and the mean clothing surface temperature is between 82 and 86 F.

The normal rate of heat production in an average sized sedentary individual is about 400 Btu per hour. The heat production for persons subjected to various rates of activity is given in Chapter 12. The human body is of complicated shape, and radiation takes place freely only from the exposed outer surfaces; there are considerable portions of the body such as the legs, arms, lower part of the head, etc., which radiate most of their heat to other portions.

It is necessary to determine the equivalent surface of the body from which heat is radiated and a similar value for convection. The total may be assumed to be about 19.5 sq ft for convection and 15.5 sq ft for radiation, in an average sized individual.

The loss by respiration and by evaporation from the nose and throat depends on the temperature and area of the moist surfaces (respiratory) of the body, the air temperature, air movement, and humidity. In air at a temperature of 70 F, this loss, for a sedentary individual of average size, will be approximately 90 Btu per hour; and at 60 F about 70 Btu per hour. These values are relative, because the total will vary materially with change of position, bodily activity, age, sex, race, etc.

The balance of the heat generated in the average human body, approximately 300 to 320 Btu per hour at about 70 F room temperature, is the approximate amount of heat given off by radiation and by convection from the external body surfaces. Under normal conditions (in still air), the radiation loss will be about 190 Btu per hour; and the convection loss about 120 Btu per hour. With an air velocity of 520 fpm, comfort will require an increase in Operative Temperature of nearly 12 deg; under such conditions the convection loss will rise to 250 Btu per hour but comfort may be attained if the subject is surrounded by heated walls which keep the radiation loss at about 50 Btu[2].

It is neither feasible nor desirable to change the relationships of convection and radiation very greatly in actual heating practice. In the laboratory, where the laws of radiative heat loss have been deduced, it is necessary to produce wide differences between radiative and convective heat loss. This can only be accomplished, however, by elaborate and powerful conditioning apparatus which simultaneously heats walls and cools air, or vice versa. Such a process would be very costly in practice and would not be justified unless marked improvement in comfort resulted from such a condition—an assumption which has not been demonstrated. In practice, where radiant heat is introduced into a room,



that heat is absorbed by surfaces, furniture, and the like, and then transformed into convective heat so that air and surfaces tend to attain a generally uniform temperature.

## OBJECTIVES OF RADIANT HEATING

Under ordinary circumstances the human being, indoors, is not subjected to marked variations between the factors affecting convection and radiation. Air and walls are not commonly very far apart in temperature; air movement and relative humidity are usually low. Where such conditions obtain, the ordinary air thermometer is a good measure of comfort—which is the reason why it has enjoyed such universal use. Where considerable window surfaces create heavy radiation loss, or where stoves or open fires, or very hot ceilings contribute to large radiation gain, the picture is changed and the air temperature productive of comfort must be correspondingly modified.

In general, however, radiant heating of occupied spaces is not a procedure designed to create differences between air and walls, but is merely one method of introducing heat into that space. The engineering factors used in determining desirable heat input will be essentially the same as if the heat were introduced by convection, or in any other way.

## PRACTICAL PROBLEMS OF RADIANT HEATING FROM A PHYSIOLOGICAL STANDPOINT

It is convenient to distinguish two different methods of introducing radiant heat into an enclosed space. The first, which may be called High-Temperature Radiation, involves direct exposure of the occupied parts of the room to radiation emitted from relatively small heating units of very high temperatures (perhaps 1,000 F); the second, Panel Heating, involves exposure to relatively large surfaces at not over 130 F.

High-Temperature Radiant Heating may be useful for temporary purposes, as in the use of a bathroom heater. It is, however, generally an undesirable process (except in rooms of great height) on account of the marked unevenness of the effect produced on the human body. Studies at the John B. Pierce Laboratory of Hygiene have shown that this type of heating produces uncomfortable differences in the temperature of different parts of the body (an over-heated head, for example, if the heat comes from the ceiling).

Panel Heating, on the other hand, is advantageous from the standpoint of temperature differentials. In actual practice, a well-designed system of this sort produces very uniform conditions, the air throughout the room differing at various points by only 5 deg. This is desirable from the comfort standpoint and may also be a factor in heat economy, since high temperatures in the upper part of the room favor excessive heat loss. The esthetic value of such a system is also considerable, since it avoids the presence of registers or free-standing radiators in the room.

In the design of Panel Heating, however, careful thought must be given to the location of the panels from the standpoint of comfort. The English commonly use the ceiling for their panels, but their rooms are generally high-studded, and outdoor winter temperatures moderate. With low ceilings even panels may produce an excessive directional heating effect if all the heat necessary in a cold climate is introduced from above. Similarly, if the floor alone is used, it may—in very cold weather—be necessary to make the floor too hot for comfort. Wall panels, or a combination of ceiling and floor panels, will perhaps produce the best results.