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SUPPLEMENTARY NOTES ON BODY RADIATION

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SUPPLEMENTARY NOTES ON BODY RADIATION[1]

By L. B. ALDRICH

WALL TEMPERATURES AND BODY RADIATION

In present-day ventilation, three basic factors are considered: (1) air temperature, (2) relative humidity, and (3) air movement. The results of my previous report indicate that, in addition, consideration should be given to a fourth factor, the temperature of the walls and surrounding objects.

For normal indoor conditions, with the surrounding objects all at the temperature of the air in the room and with the subject clothed and at rest, the radiation loss of a human subject is nearly one half of his total heat loss. This radiation emitted from skin and clothing has been shown to be nearly that of a "black body." We may assume that, by virtue of repeated reflections from the other walls and surrounding objects in a closed room, the radiation from the walls to the subject is also nearly "black." Then the radiation loss of the subject is proportional to the difference of the fourth powers of the absolute temperatures of the subject and the surroundings, in accordance with the Stefan-Boltzmann law. Suppose the mean surface temperature of a clothed subject to be 32° C. and the mean temperature of surrounding walls and objects to be the same as the air temperature, 23° C. The difference of the fourth powers of the absolute temperatures is 977×10^6. Now imagine the air temperature, humidity, and air movement to stay constant and the wall temperature to be lowered 10°. The difference of the fourth powers becomes 1963×10^6, an increase of 100 per cent in the radiation loss. On a winter day the temperature of exposed walls might easily be 10° below air temperature, and the inner surface of window panes probably would be considerably more than 10° below air temperature. Thus a subject, particularly if on the exposed side of the room, would radiate at least twice as much on one side as on the other, and his total loss of heat would be increased some 25 per cent or more.

Of even greater importance is the consideration of surrounding objects which are at higher than air temperature. As before, suppose

[1] See A study of body radiation, Smithsonian Misc. Coll., vol. 81, no. 6, 1928.

Smithsonian Miscellaneous Collections, Vol. 85, No. 11

the air temperature, relative humidity, and air movement to remain normal but let the surrounding walls be raised to a temperature of 32° C. Radiation loss from a human subject would now be negligible, the normal balance between heat produced and heat lost would be destroyed, and until readjustment is made, a condition of discomfort results. In actual schoolroom conditions, a student near an unshielded steam radiator or other artificial heat source is exposed to a temperature much higher than his surface temperature. In classes, the student is surrounded by other students and the summation of the solid angles subtended at a point on one student by the other students may be very appreciable.

As a rough example, assume a class of students placed in rows, with spaces of 2 feet between students in a row, and the same distance between rows. To simplify matters, imagine each student to be cylindrical, 1 foot in diameter and 4 feet high. The four students nearest to a given student would occupy roughly 10 per cent of the total space to which the central student is radiating. The four next nearest students exposed to the given student would occupy an additional 5 per cent, and the eight next nearest another 4 per cent. Summing up, the amount of space occupied by surrounding students would be about 20 per cent of the total space to which the central students radiate. If we reduce the space between students to only 1 foot instead of 2 and proceed to sum up in a similar manner, the area occupied by the other students increases to about 35 per cent of the whole. For a spacing of 3 feet between students it reduces to only 10 per cent. In other words, when students are spaced 1 foot apart, the total radiation loss of each student is some 35 per cent less than if he were alone in the room. When the spacing is 2 feet between students the radiation loss is 20 per cent less than if he were alone, and when the spacing is 3 feet the radiation loss is 10 per cent less. These rough figures serve in a general way to show the relationship between the spacing of students and the radiation loss of individual students.

For a given wall temperature, what air conditions produce maximum comfort? Evidently if the walls are cold an increased air temperature is indicated, and vice versa. A further study of the effect on a subject of various wall temperatures under controlled air conditions is needed. Such a study should tell us to what extent one's radiation loss may be altered without producing discomfort and should furnish evidence as to the minimum spacing advisable in classrooms without injurious reaction resulting from decreased heat loss.

ACCURACY OF SKIN TEMPERATURE MEASUREMENTS

In the study of body radiation above referred to, skin and clothing temperatures were measured by a special thermoelement device suggested by Dr. C. G. Abbot. For convenience I quote the following illustrated description of the instrument from my previous publication:

For the direct measurement of skin and clothing temperatures, a special device was prepared with the help of Mr. Kramer, the Observatory mechanician, and embodying Dr. Abbot's suggestions. The device is shown in Figure 1.[1] It consists of a specially mounted copper-nickel thermoelement of fine drawn wire. A frame of German silver is bent as shown in the figure and fastened in a wooden handle, *W*. Two silk threads are stretched to form a cross between the

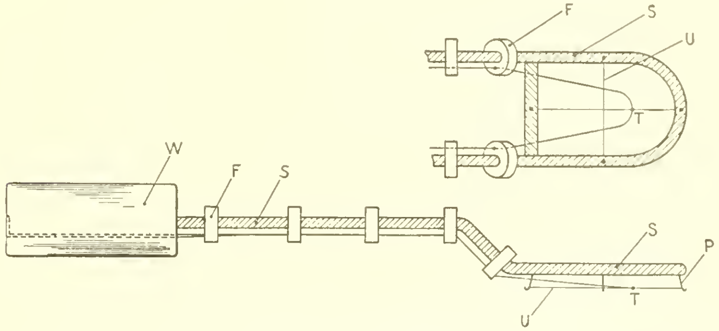

FIG. 1.—Thermoelement device for measuring surface temperatures.

F—Fibre rings. *P*—Spring steel projection.
S—German silver frame. *U*—Silk thread.
W—Wooden handle. *T*—Thermoelement.

four spring-wire posts, *p*. The thermoelement wires are fastened symmetrically to these silk threads with the junction straddling the lengthwise thread. The wires lead out through fibre rings, *F*, and through the wooden handle. The copper wire (see fig. 2) leads through a switch to a sensitive type Leeds and Northrup D'Arsonval galvanometer and thence to the constant temperature junction in a stirred kerosene bath as shown in Figure 3. The *Cu-Ni* wires are sufficiently long so that all desired positions can be reached without moving the constant temperature bath. Holding the device by the wooden handle, one presses lightly the four prongs of spring wire *p* upon the surface whose temperature is desired. This places the junction in excellent contact with the surface. There is no backing to the junction save a single silk thread, and thus no possibility of heat piling up and causing too high temperatures. For about $\frac{1}{2}$ cm. on each side of the junction, the wire also touches the surface and assumes the surface temperature, thus eliminating error due to cooling of the junction by conduction along the wires.

[1] The figure numbers of the original publication have here been changed to accord with the arrangement in this paper.

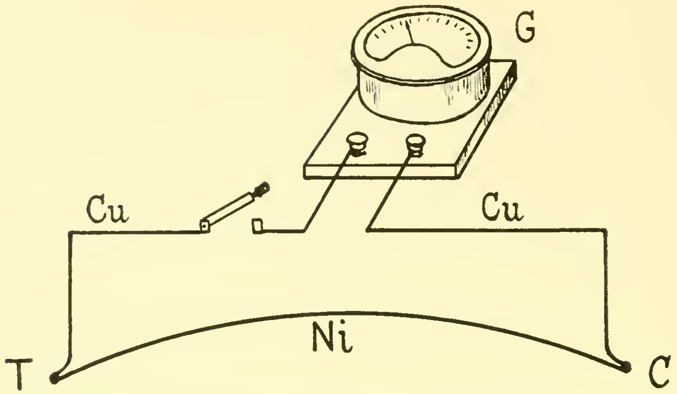

FIG. 2.—Diagram of electrical connections of copper-nickel thermoelement.

G—Galvanometer.
T—Thermoelement junction.
C—Constant temperature junction.

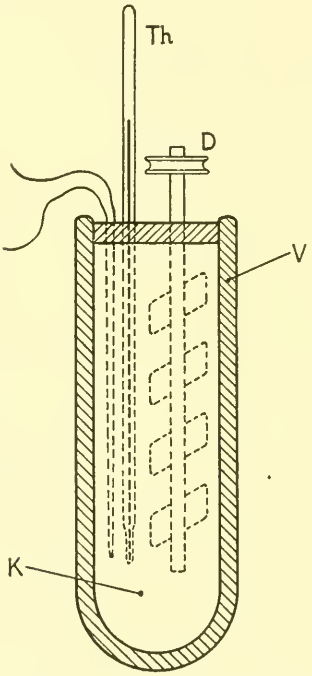

FIG. 3.—Bath for constant temperature junction.

Th—Thermometer.
D—Stirring device.
K—Kerosene bath.
V—Vacuum flask.

The instrument has recently been recalibrated. In mounting for calibration and comparison, the constant temperature junction was fastened against the bulb of a mercury thermometer. The thermometer was then inserted in a metal tube and lowered into a stirred kerosene bath, surrounded by a vacuum flask. In calibrating, the thermoelement device was placed in a well-stirred kerosene bath whose temperature was measured with a second mercury thermometer. A sensitive-type Leeds and Northrup D'Arsonval galvanometer was used with the instrument. The calibration curve, plotting galvanometer deflections against temperature differences, is nearly a straight line.

As certain systematic discrepancies had been noted between skin temperatures observed with this thermoelement and corresponding ones computed from observations of body radiation with the melikeron, it was desired to ascertain whether the thermoelement was in any considerable degree influenced by air temperatures in making such measurements. The instrument was accordingly tested in the following manner by measurements on a skinlike membrane of known temperature.

In the vertical copper calorimeter previously used (see Smithsonian Misc. Coll. vol. 81, no. 6, p. 15) three holes were made in the side at equal altitude, each 6 cm. in diameter. These holes were closed with rubber diaphragms, cemented in with waterproof cement. The thickness of the diaphragms was as follows (determined with micrometer gauge):

0.18 mm. (thinnest dental dam)
0.36 mm. (sheet rubber)
1.20 mm. (composite sheet rubber used for gaskets)

Rubber was chosen because it is pliable, simulating the surface presented by the skin or clothing. The calorimeter as before was filled with water kept thoroughly stirred and a record of its temperature determined by a mercury thermometer.

It is evident that the surface of the thickest diaphragm will be appreciably lower in temperature than the water in the calorimeter, and that the thinner the diaphragm the more closely the surface temperature approaches the temperature of the water. By obtaining a series of surface temperatures of the various diaphragms, a curve may be plotted and extrapolated to zero thickness. The more nearly correct the thermoelement temperatures, the more closely the zero diaphragm value will approach the calorimeter water temperature.

A series of comparisons is summarized in Table 1. Each value in the table is the mean of three separate determinations. Air motion was produced by a fan in the same manner as in the body-radiation experiments above referred to, and velocities (given in feet per minute) determined as before with the Hill katathermometer. Before drawing conclusions from the data in Table 1 it appeared advisable to obtain more comparisons with other thicknesses of diaphragm. Pieces of rubber of the 0.18 and 0.36 mm. thickness were stretched for several days and then cemented into the calorimeter holes previously filled by 0.18 and 0.36 diaphragms. The new thicknesses measured 0.12 and 0.27 mm. A series of comparisons with these new diaphragms is summarized in Table 2.

Table I.

Date 1929 Aug.	Room temp. C.	Calorimeter Water Temp. C.	Water temp. minus thermoelement temp. at diaphragm thickness of .18 mm.	.36 mm.	1.20 mm.	Air motion (in ft. per min.)
3	20°.50	31°.82	°.92	1°.32	2°.46	0
	21.40	32.47	1.03	1.50	1.80	
4	25.10	31.50	.73	1.10	1.43	
	26.83	28.32	.40	.40	.57	
5	20.70	35.63	1.27	2.43	3.87	
6	26.20	35.73	.97	1.70	2.20	
	24.77	33.30	.80	1.33	1.77	
10	23.27	34.00	1.27	2.73	3.97	80
	24.00	30.80	.73	1.67	2.57	
	27.80	29.83	.57	.93	1.40	
7	22.57	32.73	1.27	3.27	5.17	180
	22.43	31.97	1.20	2.90	4.63	
8	23.73	30.60	1.00	2.07	3.00	
	23.63	29.27	1.00	1.77	2.67	
	24.17	26.97	.70	1.03	1.53	
9	24.97	35.07	2.00	3.80	5.63	280
	22.30	28.30	1.20	2.20	3.07	
	23.77	26.50	.47	1.13	1.43	
	23.93	29.37	1.40	2.73	3.27	

From Tables 1 and 2, preliminary plots were made of the differences calorimeter temperature minus room temperature and calorimeter temperature minus thermoelement temperature, for each thickness of diaphragm, and for the four conditions of air velocity, viz, 0, 80, 180, and 280 feet per minute. As would be expected, the difference between the calorimeter temperature and the surface temperature determined by the thermoelement appeared to be a linear function of the difference between the calorimeter temperature and the surrounding room temperature. For each of the plots the best straight line was drawn through the points and the origin. From each of the plots values of the calorimeter temperature minus thermoelement temperature were read off at two places, 5° and 10° calorimeter temperature minus room temperature. These values were then replotted as shown in Figures 4 and 5, using thickness of diaphragm as abscissae and calorimeter temperature minus thermoelement as ordinates.

Partly from experimental error and partly because of differences in conductivity of the various diaphragms, the individual points in Figures 4 and 5 do not all lie on the curves. Smooth curves are drawn however with fair certainty. In each case the extrapolation to zero thickness yields a zero value of the difference calorimeter temperature minus thermoelement temperature. This result is gratifying since it indicates that the thermoelement device measures correctly the surface

Table 2.

Date 1929 Sept.	Room temp. C.	Calorimeter water temp. C.	Water temp. minus thermoelement temp. at diaphragm thickness of .12 mm.	.27 mm.	Air motion (in ft. per min.)
22	17°.00	24°.00	°.47	°.93	0
26	29.60	37.97	.43	.73	
28	22.87	28.47	.33	.57	
	24.63	27.70	.20	.40	
	25.97	36.67	.57	.97	
30	20.50	32.70	.93	2.00	80
Oct. 2	23.30	27.43	.40	1.30	
5	22.77	33.50	.87	2.17	
	22.30	29.63	.60	1.77	
Sept. 30	21.37	28.10	.73	1.83	180
Oct. 2	23.43	27.07	.37	1.23	
5	22.90	33.13	1.10	2.90	
	22.30	29.37	1.17	2.33	
2	23.50	26.87	.43	1.33	380[1]
5	23.07	32.53	1.10	3.97	
	22.30	29.03	1.33	2.80	

[1] This velocity was intended to be 280 ft. but through an error was found to be 100 ft. per minute too great. In Figures 4 and 5, the calorimeter minus thermoelement temperature was adjusted to an air velocity of 280 ft. per minute.

temperature. It confirms satisfactorily the substantial accuracy of the skin temperature measurements reported in my previous paper cited above.

The following conclusions also are drawn from the surface temperature measurements summarized in Tables 1 and 2:

(1) With the Smithsonian thermoelectric device, the flexibility of the surface measured is an important factor as the air motion increases. On a soft, flexible surface the instrument appears to give nearly correct temperatures for all air motions. On a stiff surface it probably reads nearly correctly for zero air motion but increasingly too low as air motion increases.

(2) In appreciable air motions, the device shows large, irregular drift, making readings difficult.

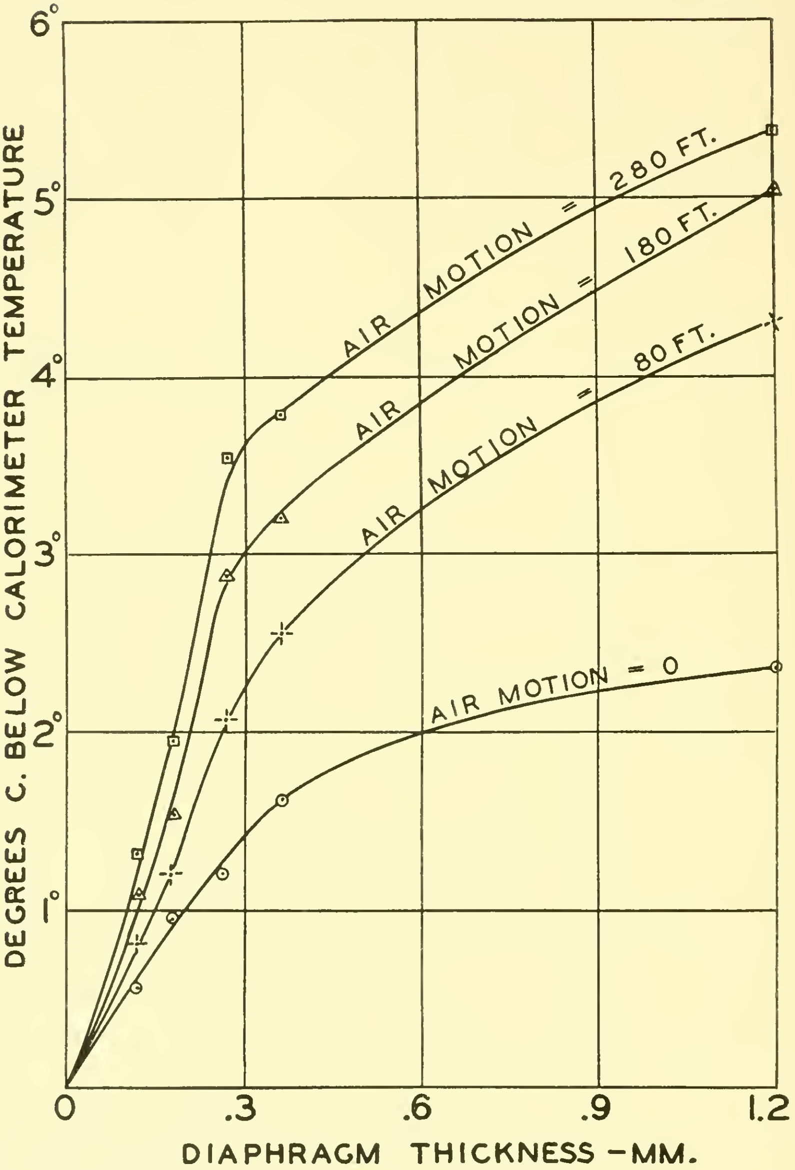

FIG. 4.—Calorimeter minus Room Temperature = 10° C.

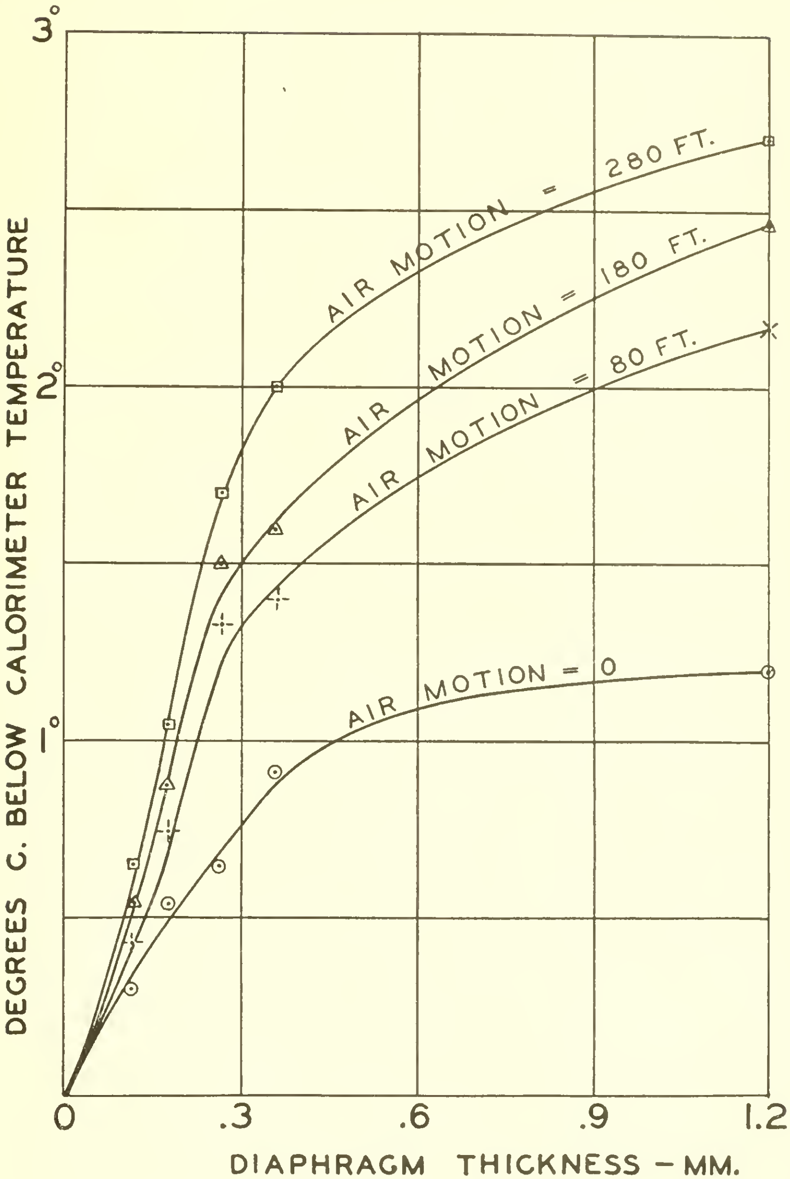

FIG. 5.—Calorimeter minus Room Temperature = 5° C.

TRANSMISSION OF RADIATION THROUGH THE SKIN

In measurements previously made comparing temperatures by the thermoelement device with temperatures computed from melikeron radiation measurements, it was noted (see Smithsonian Misc. Coll., vol. 81, no. 6, p. 19) that in measurements on the uncovered skin the computed temperatures were about 1° C. higher than those measured by the thermoelement. In measurements on clothing and calorimeter this difference appeared to be much smaller. It was thought that possibly the skin was sufficiently transparent to long-wave radiation so that the melikeron in reality received radiation from a warmer layer below the outer surface. To test the transparency of the skin the following arrangement was prepared:

Pyranometer S. I. 8 (for description and use of pyranometer see Smithsonian Misc. Coll., vol. 66, nos. 7 and 11) was mounted without glass hemisphere and with the absorbing strip vertical. A grid, cut from platinum foil and blackened, served as a source of low temperature radiation. The resistance of the grid at room temperature (22.5° C.) was 2.68 ohms. A voltmeter measured the potential fall across the grid, and an ammeter measured the current flowing. The temperature of the grid was roughly determined from its increase in resistance as computed from the voltmeter and ammeter readings. A doublewalled screen close to the grid exposed 8 sq. cm. of grid surface. The distance from grid to pyranometer was 10 cm., which permitted the interposition of two filters and a double-walled shutter.

The accepted procedure with the pyranometer is to use the first swing of the galvanometer as proportional to the incident radiation. When the shutter is opened, exposing radiation to the pyranometer strip, the galvanometer spot immediately starts to move and, if the radiation remains constant, swings to its maximum deflection in a definite time. In the galvanometer used (Leeds and Northrup Type R) this first swing required 3.53 seconds (mean of many trials). It was noticed that when certain more or less opaque filters were interposed the galvanometer spot did not start to move immediately and took appreciably longer than 3.5 seconds to reach maximum deflection. This delayed deflection was due to a combination of the direct radiation transmitted by the filter and of the radiation from the filter itself due to its increased temperature when exposed to the grid. To minimize this indirect heating effect, a stop watch was used and only those readings retained in which the maximum deflection was reached within $\frac{1}{2}$ second of 3.5 seconds. Temperatures of the grid source were varied in the range 75° to 170° C.

The ratio: $\frac{\text{deflection with a filter interposed}}{\text{deflection without the filter}}$ is a measure of the direct transmission of the filter, plus a small quantity diffusely transmitted. Tests of the transparency of various screens were made. These are summarized in Table 3.

TABLE 3.

Transmission of various substances. Temperature of source between 75° and 170° C.

Material	Thickness	% Transmitted
Rock-salt	6.0 mm.	85.
Fluorite	5.5 "	44.
Mica	.03 "	50.
Tissue paper	.03 "	About 45.
Blotting paper	.4 "	Negligible.
Hard rubber	.13 "	Very small.
Rubber dam	.17 "	Less than 10.
Lampblack	One coat, painted on rock-salt.	6 (partly due to pin holes) of rays transmitted by R. S.
Lampblack	Two coats, painted at right angles, on R. S.	Less than ½% of R. S. rays.
Camphor smoke	Smoked on R. S. plate, so thick a lamp filament is invisible through it.	20% of rays transmitted by R. S. plate.
Camphor smoke	Very thick coat, flaking off.	6% of R. S. rays.
Skin, freshly removed	About 2 mm.	Negligible.

Through the interest of a surgeon in a local hospital, a piece of human skin was obtained immediately after removal from the body. Its transmissibility was measured before it had materially lost its moisture. The piece obtained was about 2 mm. in thickness, with some fatty tissue adhering to it. When inserted as a screen in the arrangement described above, its transmissibility was found to be wholly negligible. Bazett and McGlone in a paper entitled "Temperature gradients in the tissues in man" (Amer. Journ. Physiol., vol. 82, no. 2, p. 415, 1927) have shown that in general an increase of 1° above surface temperature is found at a depth of something over 3 mm. below the skin. Forsythe and Christison (General Electric Rev., vol. 34, no. 7, p. 440, 1931) and others have pointed out that flesh, since it consists largely of water, would be practically opaque to the longer wave lengths, just as water is. It seems evident then that the higher melikeron skin-temperature values are not due to the instrument receiving radiation from deeper and warmer layers beneath the surface.

The melikeron is an instrument which responds sluggishly and is rather difficult to manipulate. Furthermore, temperatures computed from its readings depend upon the Stefan radiation constant and upon the assumption that the radiation measured is similar to that of a black body. For these reasons the melikeron-computed temperatures should not be given equal weight with those measured by the thermoelement, and the 1° difference noted may not be entirely real. There are, however, three factors each of which tends to make the melikeron skin temperature higher than the thermoelement values on the skin, namely:

(1) Due to the ridges and roughness of the skin surface, the thermoelement touches the outer and cooler parts of the ridges, whereas the melikeron views both ridges and hollows.

(2) As shown by Bazett and McGlone (loc. cit., p. 433) the temperature 1 mm. below the surface of the skin may be as much as .6° C. higher than the surface temperature. Since the outer layer of skin is scaly and comparatively dry, it may well transmit a small but appreciable amount of radiation coming from the moist and warmer layer below.

(3) Each measurement with the melikeron requires several minutes. The involuntary, psychological reaction resulting from so long an exposure of skin near the instrument aperture may tend to raise the temperature of the exposed skin.

Our conclusion then is that the 1° higher temperatures on the skin resulting in the mean from the melikeron observations would probably be reduced to about ½° if all experimental error were removed. Due to the combination of the three tendencies just mentioned, temperatures at least several tenths of a degree higher than those measured by the thermoelement appear to result from the melikeron readings on the skin.