THE RADIATION OF HEAT FROM THE HUMAN BODY

I. An Instrument for Measuring the Radiation and Surface Temperature of the Skin

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In the past few years the interest in an accurate knowledge of the temperature of the surface of the skin and of the energy radiated therefrom has greatly increased. This interest has been due on the one hand to the important part played by radiation in the theories of ventilation and on the other to the desire to make a more accurate analysis of the factors involved in human metabolism. Human calorimetry has developed to the stage where it is possible to determine accurately the total amount of heat eliminated from the body, and also, to some extent, to separate factors contributing to this total. It is generally recognized that the human body eliminates practically all of its energy from its surface in three ways, namely, by conduction and convection, evaporation of moisture, and radiation. These factors are variable depending upon the condition of the individual and upon the surrounding environment. Aside from the losses due to vaporization, the energy from the body, liberated by radiation and conduction, probably follows Newton's cooling law and for that reason the temperature of the surface of the body is of physiological importance. Therefore in order that a possible relation between the metabolic rate and surface temperature and radiation may be investigated it is necessary that experiments be carried out with an instrument which will measure these latter quantities accurately and in absolute value. It is believed, for reasons to be discussed in the next paper (1), that a radiometric device, which depends upon the absorption of the radiant energy of the skin for its indications, is the simplest and most accurate instrument for the measurement of skin temperature and radiation. The present design of instrument is described with its technique because it offers several advantages over previous designs so far as accuracy and general simplicity are concerned.

The use of a radiometer [1] for the measurement of radiation and skin temperature is now some twelve years old, having been first employed by

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[1] The term "radiometer" is employed in this paper to refer to any device for measuring radiation and not alone to the physical instrument generally known by that name—the physical instrument of Crookes.

Aldrich (2, 3) in 1922 and later by Cobet and Bramigk (4) and by Bohnenkamp and Ernst (5).

These instruments all require the use of a very sensitive galvanometer and thus they are not suitable for general use. The devices of Aldrich and of Cobet and Bramigk are adapted to the measurement of skin temperature and that of Bohnenkamp and Ernst to measurement of body radiation. Recognizing the desirability of using a radiometer for general measurements of this kind the present apparatus, measuring at the same time skin temperature and body radiation, was designed to be rugged, simple, and accurate.

The apparatus as assembled for use on a rolling table is shown in the photograph, Figure 1. An idea of the size of the device can be had from the upper scale of the slide rule, S, which is marked off in centimeters; the whole slide rule is 12 inches long. The apparatus consists essentially of three parts, the radiometer, R, the galvanometer, Ga, and the potentiometer, P.

The galvanometer is a product of Leeds and Northrup and is listed in their catalogue as Number 2400, with a sensitivity of 10 micro-volts per division. Instead of the usual telescope, a light has been mounted in place of the eyepiece and an index is projected upon the scale, GS, so that the galvanometer deflection is much easier to observe.

The potentiometer is of my own design and was built in this laboratory by Mr. G. F. Soderstrom. A wiring diagram of the circuit is shown in Figure 2. The current through the one ohm coil at 'output' is determined by the current through the milliammeter and the resistances v or v'. When the switch S_1 is thrown to put v or v' in the circuit the voltage across the output coil is 10^{-4} or 10^{-5} volts respectively. The switch S throws the variable rheostat R in parallel with either v or v' so that any arbitrary voltage can be produced across the output coil per milliampere, depending upon the setting of the rheostat. The rheostat is so set upon calibration that the milliammeter reads one millampere for each small calorie of radiant energy $\times 10^{-4}$, per second per cm². The resistance coils for the potentiometer are wound of constantan wire so that no trouble is encountered while using the instrument within the usual range of temperatures. The flexible leads to the radiometer are marked $F.R.$

The radiometer itself consists of two parts shown in Figure 1, the radiation sensitive device, R, and the room temperature black-body, $R.T.B.$, or cold body. This latter is an aluminum block which is painted black and which serves as a reference body for the radiometer. Its temperature is determined by means of a right-angle mercury thermometer, T, attached to the block. The temperature of this block is not kept constant but changes with the room temperature and unless some large, rapid fluctuation occurs it can be considered as at the temperature of the room.

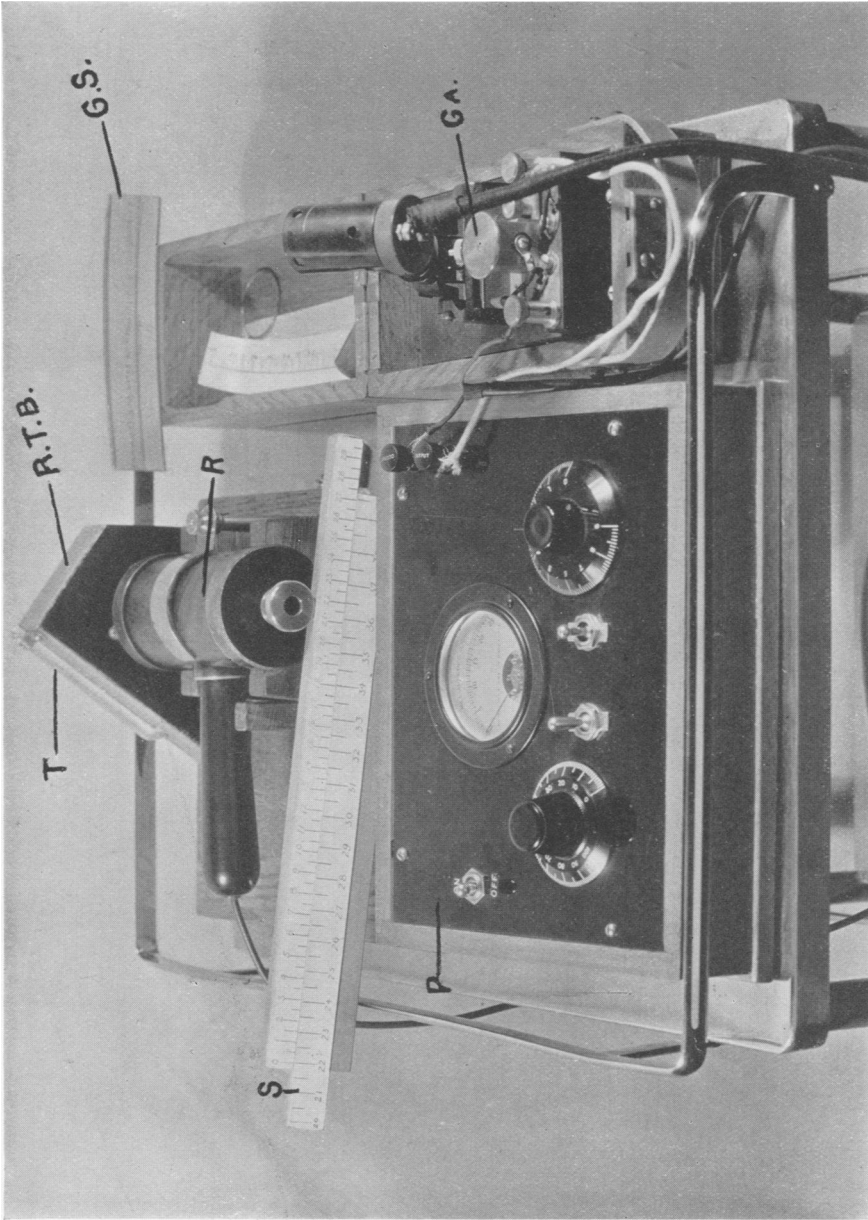In Figure 3 is shown a vertical section of the radiation device together

Fig. 1. Radiometric Surface Thermometer Assembled for Use

with the calibration set, or Leslie Cube.   The outside casing of the radi-
ometer is a cylindrical brass tube, one end of which is closed with a metal
cap and the other end partially closed by a metal ring into which are
screwed four metal feet provided with amber tips.   The inside casing is a
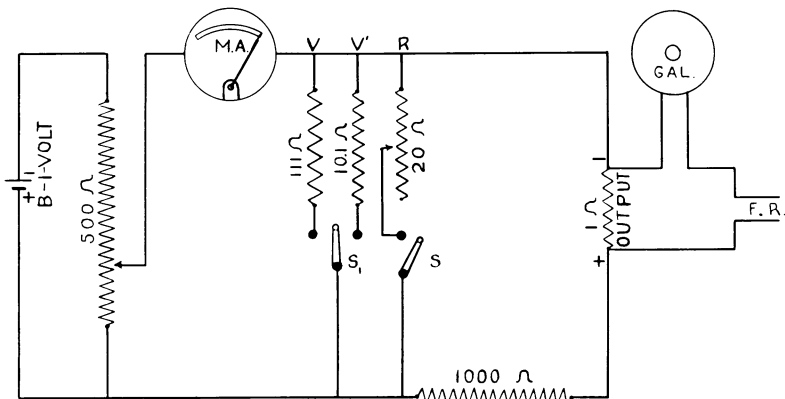fiber tubing which is separated from the metal tube by a ring of cork.   This

FIG. 2.   WIRING ARRANGEMENT FOR POTENTIOMETER

fiber tube is closed at one end by a fiber block which serves as the support
for the thermocouples, *T*.   Directly in front of the thermocouples is placed
a thick fiber block in the center of which is fitted a silver cone, *C*, for con-
centrating the rays upon the thermocouples.   There is no shutter or foreign
medium between the thermocouples and the skin.   In the upper left corner
of the same figure is shown a detailed diagram of the thermocouple arrange-
ment in plan.   The stippled rings are the fiber supports over which is
stretched a thin (1 mu) film of nitrocellulose, *N*.   This film gives added
support to the thermocouples without changing the radiation characteristics
of the thermopile.   The radiation thermopile consists of four junctions ar-
ranged in the form of a disc as shown at *T*.   The disc is of tinfoil and is
divided into four parts so that each junction is insulated from the other
three.   The cold junctions, *J*, are arranged symmetrically about the radia-
tion junctions outside the range of the incident radiation.   The elements of
the thermocouples are the Hutchins bismuth alloys (95 per cent Bi—5 per
cent Sn and 97 per cent Bi—3 per cent Sb) and are made by myself ac-
cording to a method devised by Professor A. H. Pfund of Johns Hopkins
University, Baltimore.   (Professor Pfund informs me that he is shortly
to publish a full account of his new technique for thermopile construction.)
The elements are welded together mechanically and the tin foil receivers
welded to the junction of the two elements.   The thermoelectric power of
the thermocouples is approximately 130 microvolts per degree, and this
combination of metals is now used quite extensively in sensitive radiation

devices. The cold junctions serve in a compensatory character and, while not affecting the radiation readings, help in maintaining a constant zero position in the galvanometer and minimize the effect of stray disturbances. The metal disc has a diameter of 9 mm. and its surface is blackened by depositing bismuth-black in a vacuum. This metal black is totally absorbing for all wave lengths in the visible and near infra red but becomes more reflecting as the wave length increases, so that at 10 mu, where the maximum of body radiation occurs, it absorbs only about 60 per cent of the incident energy. Several other blackening materials were experimented with but none were found to be as satisfactory as bismuth-black. The introduction of the silver cone in front of the thermopile increases its sensitivity about ten times so that the instrument can be used with the relatively insensitive portable galvanometer. The instrument can be handled freely and air currents, etc. have little effect upon it.
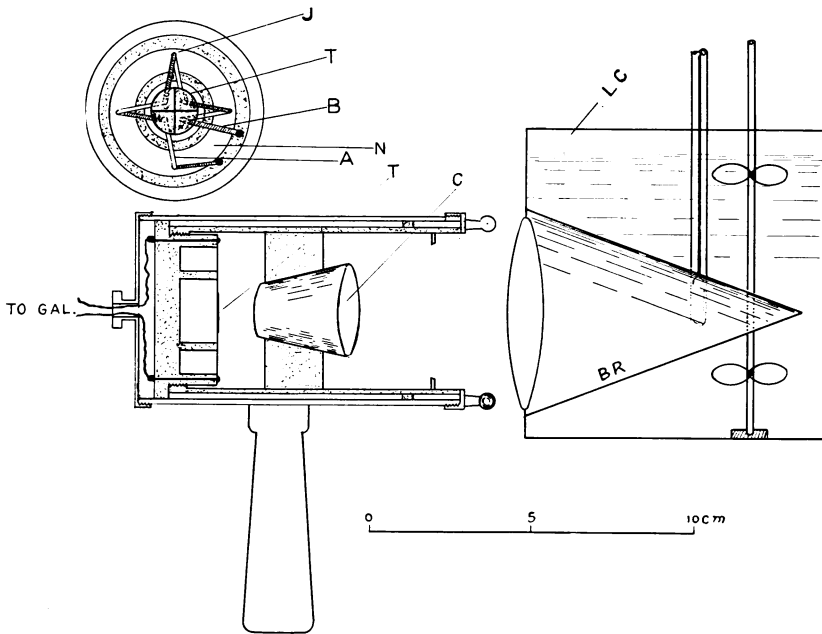

FIG. 3. VERTICAL SECTION OF RADIOMETER (LOWER LEFT) AND LESLIE CUBE (RIGHT). DETAIL OF THERMOPILE CONSTRUCTION (UPPER LEFT)

The Leslie Cube, LC, is shown to the right of the radiometer in Figure 3. This radiation standard consists of a metal cube 10 cm. on an edge with a hole 7 cm. in diameter in one side over which is fitted a copper cone, BR, extending into the cube. The cone is painted black with a glossy paint so that one looks into the base of the cone as if looking into a deep hole. The cube is provided with a stirrer and thermometer, and for a calibration is

filled to a level above the cone with warm water. The temperature of the surface of the cone is assumed to be at the same temperature as that of the water in the cube. This assumption seems to be justified by the fact that the heat losses per unit area of the conical surface are small. Thus the cone serves two important purposes, that of being a very efficient black-body radiator and being so arranged that its temperature can be easily measured. Actual tests show that readings on the cone, whether the cube temperature be above or below room temperature, are perfectly consistent, confirming the assumption that the temperature of the conical surface is practically that of the water of the cube.

The technique of calibration is as follows: The radiometer is placed in its holder (see Figure 1) so that the thermocouples are facing the blackened surface of the $R.T.B.$ The temperature of the $R.T.B.$ is noted and the galvanometer index is set to zero. The switch of the potentiometer battery is open so that no e.m.f. is imposed across the " output " coil. The radiometer is then placed in the position indicated in Figure 3, and the temperature of the water in the cube noted. The deflection of the galvanometer is balanced off by means of the potentiometer, which has been adjusted so that the switch, S, has connected the variable rheostat in the circuit. The energy radiated from the cone per unit area of its base is computed from the Stefan-Boltzmann formula,

$$S = S_0 \ (T^4 - T_0^4) \tag{1}$$

where, S = radiation emitted in small calories per second per square centimeter of surface (on the surface base).

S_0 = Stefan-Boltzmann constant = 1.37×10^{-12} small cal/sec/cm^2.

T = the absolute temperature of the cube = $273 +$ deg. C.

T_0 = the absolute temperature of the $R.T.B.$

This calculation can be quickly done graphically by means of the slide rule which is shown at S in Figure 1. The rule is made up of two scales one proportional to the calories of heat radiated by the cube and the other proportional to the centigrade temperature of the cube as computed from the above formula. This mechanical monograph is a great time saver in the matter of calculation. Thus, by setting the cold body temperature on the zero of the energy scale, one reads off the energy that should be indicated by the potentiometer, by noting the energy which corresponds to the cube temperature. As an example, consider the setting of the slide rule shown in Figure 1. The upper scale is the energy or caloric scale and the lower the temperature scale. The zero of the energy scale is set for $R.T.B.$ temperature of 22° C. Let us suppose that the cube temperature is 34.5° C., then the milliameter of the potentiometer should read 18.75 milliamperes corresponding to a radiation of 18.75×10^{-4} small calories per second per cm^2. If the reading in milliamperes does not equal the number of calories

emitted by the cone, the variable rheostat is adjusted until the two coincide. The calibration is then finished and as many points as desired can be taken to check the setting of the rheostat. For the present design of radiometer, a radiation of 10^{-3} small calories per second per cm^2 from the cone will produce 150 mm. deflection upon the galvanometer, corresponding to a voltage of 2×10^{-4} volts. A calibration usually takes about one minute so that a calibration check is carried out before each day's work. The setting of the rheostat can be trusted for several weeks.

The potentiometer is employed in order to make the results independent of the galvanometer, which is used only as a null instrument. However, if readings are to be made within a small range of room temperatures the galvanometer can be trusted as a deflection instrument. In this case, a galvanometer scale is drawn so that the deflection of the galvanometer can be read directly in calories or in temperature. This method is not quite so precise as that with the potentiometer, but, with sufficient care, temperature can be read in this manner with an accuracy of about $\pm 0.2°$ C.

The indications of the galvanometer and of the potentiometer are proportional to the energy exchange between the cube and the $R.T.B.$, and therefore the readings are usually made in terms of energy and converted by the 'slide rule' into temperature. The temperature difference between the $R.T.B.$ and the cube is not proportional to the deflection of the galvanometer except for very small temperature differences. This is to be expected from the expansion of the Stefan-Boltzmann formula.

$$S = S_0 \ (4T_0^3 \ \overline{\Delta T} + 6T_0^2 \ \overline{\Delta T^2} + \overline{4T_0} \ \Delta T^3 + \overline{\Delta T^4}),$$

where $\Delta T = T - T_0$.

As long as ΔT is small compared to T_0 all the terms except the first may be neglected, but for ΔT as large as $10°$ C. the second degree terms are appreciable and errors as large as $0.5°$ C. may be made by neglecting the deviation of the temperature curve from a straight line. Cobet and Bramigk (4) state that the temperature calibration curve for their radiometer was a straight line in contradiction to the above statements. Should their device have been as accurate as reported, $\pm 0.1°$ C., it would seem impossible that they should not have detected the deviation mentioned, since, at $\Delta T = 10°$, it amounts to $0.5°$ C. The fact that their instrument measures the temperature difference between the hot source and the movable shutter, whose temperature is not accurately known, probably accounts for the discrepancy. A shutter was built into the present radiometer in a manner very similar to that of Cobet and Bramigk, but it was found to introduce appreciable uncertainties into the results. To take the place of the shutter the $R.T.B.$ was designed so that the radiometer simply compares the radiation of the skin or Leslie Cube with that of the $R.T.B.$ whose temperature is known.

In Figure 4 is shown a photographic registration of the galvanometer deflections. The baseline shows that the $R.T.B.$ was at a temperature of 24.8° C. and the temperature of the cube is indicated by the ordinates along with the energy exchange. The abscissae indicate that about eighteen or twenty seconds is required for a reading. In fact, 98 per cent of the final value is reached in this time.
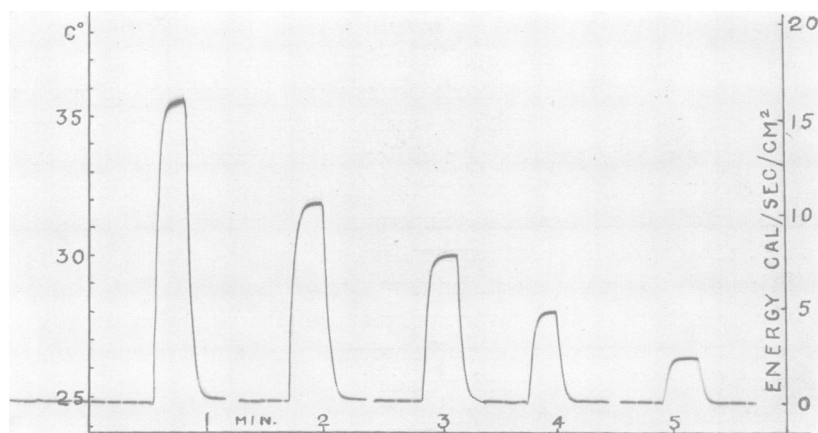

FIG. 4. PHOTOGRAPHIC REGISTRATION OF RADIOMETER CALIBRATION

The calibration of the instrument is easily accurate to ± 0.05° C. but the usual readings made upon subjects are accounted accurate to ± 0.1° C. and the energy readings to ± 0.1 × 10⁻⁴ small cal/sec/cm². The measurement which is made is the transfer of energy from the skin to a black-body at room temperature and in this process the radiometer plays only the rôle of a comparator and does not make any absolute measurement in itself. (The rise in temperature of the radiation junctions, when the instrument is in use does not invalidate this statement.) Without this technique, many instrumental constants, among them the absorbing power of the blackening material with which the radiation junctions are covered, would enter as a correcting factor. These complications of the data are avoided by making the radiometer play the part of a 'thermo-level' which compares the thermometric level of the skin with that of the R.T.B. whose temperature is known. This technique is similar to that used by Aldrich.

In order that the technique of the 'thermo-level' be checked as to absolute value of the radiation, tests were made using a radiation standard furnished by the U. S. Bureau of Standards. The comparison between the radiation standard and the Leslie Cube calibrations can be more easily made if the geometry of the radiometer be made as simple as possible. To this end the condensing cone in the radiometer was replaced by a diaphragm of appropriate size as shown at A in Figure 5. Then the radiation coming

from the cube is restricted to a cone of rays and the energy received by the
thermocouples can be calculated by use of the Stefan-Boltzmann and Lam-
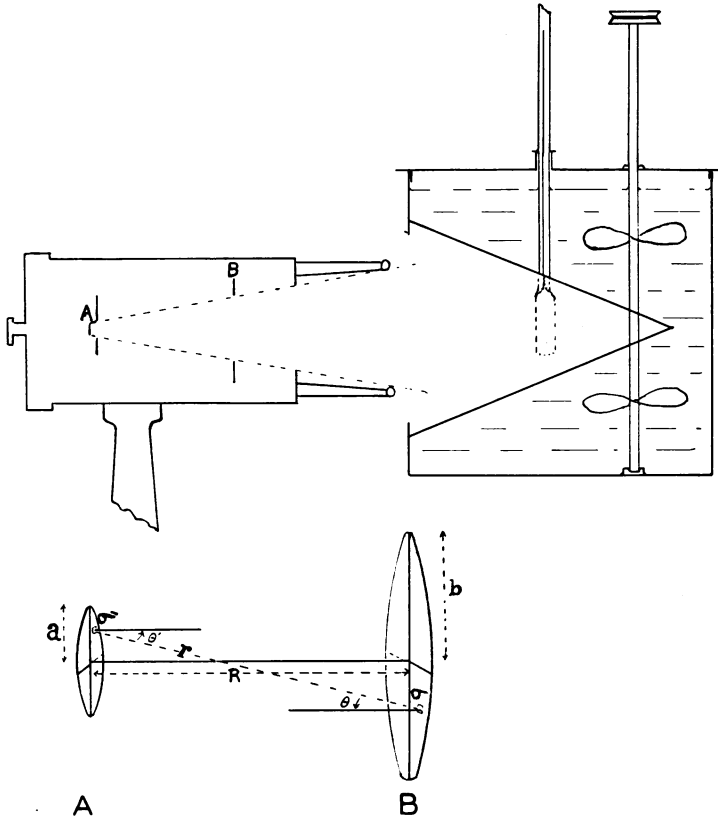bert cosine laws. The result is obtained by considering the transfer of

FIG. 5. DIAGRAM FOR CALCULATION OF ENERGY RECEIVED BY
THERMOPILE FROM LESLIE CUBE

energy between the two plane, parallel, circular surfaces A and B, A being
the area of the thermocouple disc and B the area of the diaphragm.   Inte-
gration yields as the result,

$$Q = \frac{S}{\pi} \frac{AB}{R^2} \left(1 - \frac{a^2 + b^2}{R^2} \right),$$ (2)

where Q = interchange of energy between the Leslie Cube and the $R.T.B.$
 S = defined in Equation 1.
 R = distance of thermocouple from diaphragm.
 a = radius of receiving surface A.
 b = radius of emitting surface B.

The values of Q, obtained by changing the temperature of the Leslie Cube, are then plotted against the e.m.f. developed by the thermocouples, and compared with the curve obtained with radiation standard under the condition prescribed by the Bureau of Standards. Table I shows the results of a calibration comparison between the radiation standard and the Leslie Cube.

TABLE I

Calibration against standard lamp and Leslie Cube

	S	E.M.F.	S/E
	cal/sec/cm ^{2}	*volts*	
Standard lamp..................	1.20×10^{-4}	32.6×10^{-7}	36.8
Standard lamp..................	1.75×10^{-4}	47.0×10^{-7}	37.2
Standard lamp..................	2.45×10^{-4}	67.0×10^{-7}	36.6
Standard lamp..................	3.20×10^{-4}	86.5×10^{-7}	36.9
Leslie Cube....................	3.70×10^{-4}	100×10^{-7}	37.0
Leslie Cube....................	10.2×10^{-4}	273×10^{-7}	37.4
Leslie Cube....................	15.5×10^{-4}	417×10^{-7}	37.2
Leslie Cube....................	20.4×10^{-4}	558×10^{-7}	36.6
Leslie Cube....................	25.2×10^{-4}	682×10^{-7}	36.9

The consistency of the values in the last column show that the results obtained by " thermo-level " technique are correct in absolute value as well as relatively.

The technique of making the skin temperature measurements is similar to that for making the calibration. The radiometer is pointed at the $R.T.B.$ while the galvanometer index is set to zero and the temperature of the $R.T.B.$ is recorded. The instrument is then placed over the part of the skin whose temperature is desired. The full aperture of the radiometer which is included within the four amber tips (the area included within a circle 5 cm. in diameter) must be filled in order that the measurement can be made. This area, of 20 cm², is arbitrary and by altering the design, can be made smaller (10 mm²), or larger as desired. The present arrangement is not adapted to the measurement of the skin temperature of a single finger or toe or other limited area except as averaged in with the surrounding areas. As soon as the instrument is placed on the skin the galvanometer will deflect and after twenty seconds will reach a point of equilibrium. The deflection is balanced to zero by means of the potentiometer whose reading, in calories, is recorded. The calorie readings can then be converted into temperature by means of the slide rule mentioned before.

The detailed measurements on normal subjects included in the stimulating papers of Bohnenkamp and Ernst (6) offer the only possibilities in the literature for a comparison of measurements made by the radiometer with those by other investigators. Bohnenkamp and Ernst point out the fact that the radiation from the forehead is very constant in all normal per-

sons, and they give the value of 1.18×10^{-9} cal/sec/cm^4 as being the average. Converting this into the form of S (small cal/sec/cm^2), Equation 1, this value becomes 3.17×10^{-2} small cal/sec/cm^2 corresponding to a skin temperature (160° C.) 320° F. The corresponding value obtained with the radiometer under similar circumstances is $S = 1.50 \times 10^{-3}$ small cal/sec/cm^2, skin temperature = (34.9° C.) 96° F. An examination of the data in the paper of Bohnenkamp and Ernst shows that their radiation values are on the average 17 times those obtained with the radiometer. The computations which lead from these data to their very reasonable result, that their subject lost 70 per cent of her basal heat through radiation, were gone over,[2] and it appears that a factor of approximately $2\,\pi^2$ (19.6) was lost in the calculation. Their errors, therefore, probably originate in their radiometric device. Their whole method of calculation of the projection surface area of the body is very fine, but their technique in the measurement of radiation is questionable and provides possibilities of errors of the magnitude mentioned above.

When the radiometer is placed before the warm skin or Leslie Cube for any length of time the inner structures of the instrument are warmed and on account of their re-radiation produce an additional deflection upon the galvanometer. Upon replacing the instrument before the cold $R.T.B.$ it is found that the index does not return quite to the zero position. This effect is not observed for temperature differences less than 5° C. or when the radiometer is referred after each observation to the $R.T.B.$ It is often desirable, however, to make a series of measurements without going to the trouble of referring the radiometer to the $R.T.B.$ after each reading. In order to do this the radiometer is first warmed up to the temperature level which is to be investigated, by allowing it to point at the skin of the subject for one minute before an observation is to be taken. Then the instrument is referred to the $R.T.B.$ the index of the galvanometer adjusted to zero, and the radiometer put into use immediately. Usually the whole surface of the body can be investigated in one series of readings with the exception of cold extremities. To examine the cold extremities the radiometer is replaced in front of the $R.T.B.$, the zero position checked, and the hands and feet examined as rapidly as possible. Tests have shown that no appreciable error is introduced by such a procedure. There is no danger of mistaking the slow rise in deflection due to the heating of the instrument with that due to the heating of the thermocouples, and a very definite equilibrium point is reached in each case.

There are several items of theory concerning the determination of skin temperature by means of a radiation device, such as the radiating power of

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[2] The calculations of Bohnenkamp and Ernst as well as my own were carefully checked by Dr. Grundfest of the Department of Physiology, Cornell Medical College and by Dr. K. Hartline of the Johnson Foundation, University of Pennsylvania Medical School. The author is greatly indebted to Dr. Grundfest and Dr. Hartline for their kindness.

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the skin, the variability of the skin temperature within the area examined, etc., which will be discussed in Part II of this series (1). The instrument is introduced here in a form that is adapted rather to general clinical use than to experiments dealing with such theoretical problems. It is believed that the present design of instrument has several disadvantages, such as its size (11 cm. long) which makes examination under clothing, etc. difficult; the fact that a small area of skin cannot be observed; and the warming up of the instrument which necessitates pre-heating which is rather inconvenient at times.

The radiometer readings give the skin temperature accurately ($\pm$ 0.1° C.), and the values can be depended upon both as to their relative and absolute values. At the same time the energy radiated from the portion of skin examined can be determined. It is hoped that further experiments will relate these values to the total loss of energy and to the basal metabolic rate. The instrument is rapid and easy to use, and although it is still in the experimental stage as regards its manufacture, its cost should not be exorbitant. It is believed further that all of the objections listed above are due rather to faulty details of the present design of instrument than to the fundamental idea upon which the device is constructed.

SUMMARY

A radiation device for measuring skin temperature and radiation is described which has the advantages over previous similar devices of higher sensitivity, greater accuracy, and simplicity. The device is relatively small, portable, easily handled and accurate to $\pm$ 0.1° C. and $\pm$ 0.1 small calorie per second per square meter of radiation, in absolute as well as relative value. The technique of calibration and of measurement of skin temperature is described together with a mechanical nomograph for calculations of the Stefan-Boltzmann Law.

BIBLIOGRAPHY

1. Hardy, J. D., The radiation of heat from the human body. II. A comparison of some methods of measurement. J. Clin. Invest., 1934, **13**, 605.
2. Aldrich, L. B., The Melikeron—An approximately black-body pyronometer. Smithsonian Misc. Col., 1922, **72**, No. 13.
3. Aldrich, L. B., A study of body radiation. Smithsonian Misc. Col., 1928, **81**, No. 6.
4. Cobet, R., and Bramigk, F., Über Messung der Warmestrahlung der menschlichen Haut und ihre Klinische Bedeutung. Deutches Arch. f. klin. Med., 1924, **144**, 45.
5. Bohnenkamp, H., and Ernst, H. W., Untersuchungen zu den Grundlagen des Energie- und Stoffwechsels. II. Über die Strahlungsverluste des Menschen. Arch. f. d. ges. Physiol., 1931, **228**, 63.
6. Bohnenkamp, H., and Ernst, H. W., Untersuchungen zu den Grundlagen des Energie- und Stoffwechsels. I. Über die Strahlungsveluste des Mensch I. Arch. f. d. ges. Physiol., 1931, **228**, 41.