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A NEW FORM OF THERMOELECTRIC RECORDING PYRHELIOMETER.

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[Weather Bureau, Washington, April 12, 1923.]

SYNOPSIS.

A thermopile consisting of 50 couples is made from 60Au–40Pd with 90Pt–10Rh wire 0.0016 inch in diameter, by electrically fusing the junctions. Alternate junctions are attached to, but electrically insulated from, two thin concentric copper rings. The inner ring has its upper surface painted black; the outer ring, white. Details of construction are given.

When exposed to solar radiation, the excess in temperature of the junctions attached to the blackened ring over those attached to the whitened ring produces an electric current, the voltage of which is very nearly proportional to the intensity of the solar radiation. With a solar radiation intensity of 1 gram-calory per minute per square centimeter of surface the current generated has a voltage of between 9 and 10 millivolts.

A type RM Engelhard recording voltmeter is employed to obtain continuous records of the solar radiation intensity. A sample record and illustrations of the thermopile are given.

THERMOELECTRIC PYRHELIOMETERS.

The use of a thermopile for measuring the intensity of solar radiation is not new. The Ångström pyrheliometer [1] and the Smithsonian pyranometer [2] are well-known instruments of this type.

Recently Dorno [3] has described an instrument employing the thermopile for obtaining continuous records of the intensity of direct solar radiation. He also refers to an adaptation of the thermopile described in an earlier paper,[4] for continuously recording the total radiation (direct solar + diffused sky radiation) received on a horizontal surface. Both these instruments develop thermoelectric current of such low voltage that the photographic registration of the deflection of a sensitive galvanometer is the only practicable way of obtaining a record. In his later paper, however, Dorno [5] refers to a "miniature thermocouple of 12 elements of special alloys, which, when fully exposed to the sun, gives about 4 millivolts, a power which would enable us to replace the photographic by a mechanical registration."

THE WEATHER BUREAU THERMOELECTRIC RECORDING PYRHELIOMETER.

The Weather Bureau, in cooperation with the United States Bureau of Standards, has recently designed, and its mechanicians have constructed, a very convenient form of thermoelectric recording pyrheliometer, which, when exposed to full sunshine, is capable of developing about 15 millivolts. It seems desirable, therefore, to describe it in some detail.

[1] Ångström, Knut., The absolute determination of the radiation of heat with the electric compensation pyrheliometer, with examples of the application of the instrument. Astrophysical Journal, vol. 9, pp. 332–346.
[2] Abbot, C. G., Fowle, F. E., and Aldrich, L. B., Annals of the Astrophysical Observatory of the Smithsonian Institution, vol. 4, pp. 65–76.
[3] Dorno, C. Progress in radiation measurements. MO. WEATHER REV., Oct. 1922, vol. 50, pp. 515–521.
[4] Ångström, A., and Dorno, C., Registration of the intensity of sun and diffused sky radiation. MO. WEATHER REV., March, 1921, vol. 49, pp. 135–138.
[5] loc. sit., p. 516.

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Thermoelectric couples.—Experience with the pyrgeometer [6] has shown that while silver-bismuth thermoelectric junctions are highly efficient, they are difficult to solder, and the bismuth wire is liable to break with ordinary handling of the instrument. Upon the advice of the Director of the Bureau of Standards a combination of the alloys 60Au–40Pd with 90Pt–10Rh was tried.

Under test at the Bureau of Standards, a thermocouple made up of these two alloys gave the following electromotive force when the fixed junction was in ice and the other junction was at the temperature indicated.

Temperature, °C.	E. M. F., millivolts.
100	3.68
60	2.12
25	.85
–40	–1.24

The following equation gives the relation between temperature and the electromotive force if E is in microvolts and t in degrees centigrade.

$$E=32.975t+.03881t^2$$

The mean temperature-resistance coefficients per degree centigrade between 0° and 100° were found to be—

Wire.	Temp.-resist. coefficient.
Platinum-rhodium	0.00165
Gold-palladium	.000446

Measurements at the Weather Bureau gave the resistance per linear foot of wire 0.0016 inch in diameter at room temperature as follows:

	Ohms.
Platinum-rhodium	50.7
Gold-palladium	54.6

It thus appears that while, as compared with Bi-Ag, these alloys give little more than half the E. M. F., they have less than half the resistance, and should give slightly better current sensitivity. Moreover, these alloys are very ductile, which permits them to be drawn out to a small diameter. They also fuse readily, making a neater junction than soldering.

Thermopiles.—Heretofore in the design of multiple thermocouple devices for measuring radiation it has been the practice to secure the needed surface for the larger number of junctions by resorting to the use of several parallel strips with alternating black and bright surfaces.

The disadvantages of such construction and the difficulties of computing the performance of such forms have been obviated by the use of the annular ring and disk arrangement. This greatly improved and simplified design, which also secures proper exposure for the composite surface, was suggested by Professor Marvin, and is easily understood from the description which follows.

[6] Kimball, H. H., Nocturnal radiation measurements. MO. WEATHER REV., Feb., 1918, 46: 56–70.

On the left in Figure 1 is shown the upper surface of the black ring, *C*, and the white ring, *D*. The space inside the black ring is filled by a whitened disk, and the rings are mounted inside a bakelite ring, also painted white. The upper surfaces of the disk, the two rings, and the bakelite ring are in the same plane.

On the right in Figure 1 is shown the under side of the rings *C* and *D* with the wires forming the couples attached. It will be noted that each ring rests on the ends of three wire supports to which it is cemented by bakelite lacquer. The central disk is supported on a post rising from a metal strap attached to the lower side of the bakelite ring.

The space between the disk and the inner ring *C*, between the two rings, and between the outer ring *D* and the bakelite ring, should be just sufficient to insure insulation.

Two thermopiles were made up of wire 0.0008 inch in diameter. No. 1 had 20 couples, and a resistance at room temperature of 137 ohms. No. 2 had 40 couples so arranged that they could be connected in series, or in two parallel series of 20 couples each. The resistance of No. 2_s (40 couples in series) was 326 ohms, and of No. 2_p (two parallel series of 20 couples each), 82 ohms.

A circular projection, *P*, on the surface of the block, just fills the space between these two rings and holds them in place.

Single junctions of the two wires are made, preferably while the wire is still attached to the spools, by twisting the ends together, and electrically fusing them. One terminal of the circuit carrying the heating current may be attached to tweezers, between the points of which the twisted wire is clasped. The other terminal, consisting of a finely sharpened carbon pencil, is brought in contact with these wires. A 110-volt circuit, in which the current is stepped down by resistance to about 1 ampere, will burn the wires back to the tweezers and there form a small bead. They are then cut off at the proper length and laid aside until the required number of junctions has been prepared.

The surfaces of the copper rings *C* and *D* are thoroughly polished, cleaned, and lacquered with bakelite lacquer. For cementing the junctions to the rings bakelite lacquer, insulating bakelite varnish, or shellac may be used. The junctions are attached to the inner ring *C* by pressing them against the cement, one junction for each alternate division on the brass block, and then covering the junction with the cement.

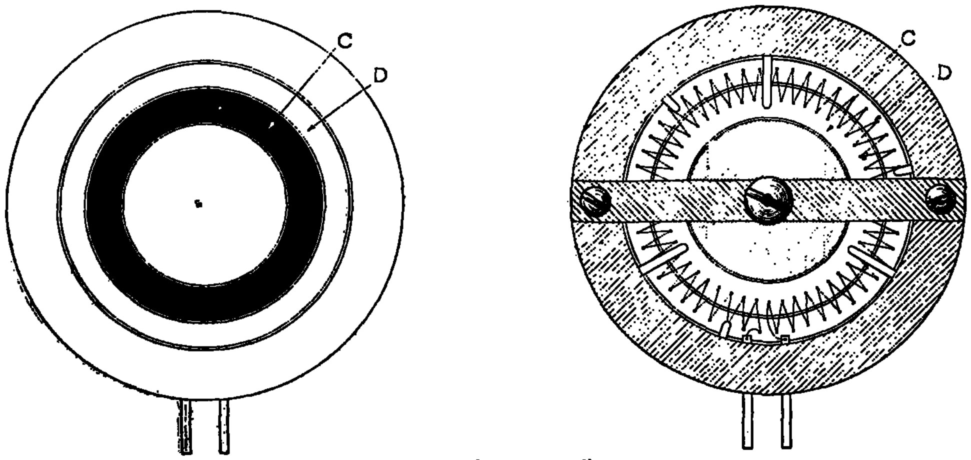

FIG. 1.—Details of thermopile.

When exposed in a diaphragmed tube to solar radiation of an intensity of 1.37 gram-calories per minute per square centimeter, No. 1 developed an E. M. F. of 5.10 millivolts; No. 2_p, 5.49 millivolts; and No. 2_s, 10.65 millivolts. The moving coil in the voltmeter employed had a resistance of about 91 ohms. Therefore, No. 2_p, on account of its low resistance, gave a current of much greater amperage, and consequently caused a greater deflection of the voltmeter, than Nos. 1 and 2_s.

Thermopiles Nos. 3, 4, and 5 were made of wire 0.0016 inch in diameter, and with 50 couples in series. The construction of these thermopiles will now be described.

Details of construction.—Figure 2 shows a brass block with its upper surface divided by radial lines into 100 equal spaces. On this block are placed the two copper rings, *C* and *D*, shown in Figure 1, and which have the following dimensions:

	Inches.
Thickness (No. 25, U. S. standard sheet steel gauge)	0.021
Inner diameter of *C*	0.88
Outer diameter of *C*	1.23
Inner diameter of *D*	1.25
Outer diameter of *D*	1.52

These dimensions give a surface area of about 0.57 square inch or 3.67 square centimeters to each ring.

The wires of the individual couples having been identified, the loose end of an Au-Pd wire of one couple is twisted to the Pt-Rh wire of an adjacent couple, fused, and then fastened to the outer ring *D*, a junction for each alternate space on the block, using the spaces left vacant by the junctions attached to the inner ring.

The fusing of these second junctions is effected as follows: The brass arm *A*, Figure 2, revolves about the central post *X* of the brass block and is lacquer coated or insulated except for a small spot on the lower point of the end at *E*. The ring *D* is also lacquer coated. One terminal of the 110-volt circuit is placed in contact with the lower surface of the brass block; the other, or carbon terminal, is brought in contact with the twisted wires. If the lacquer-free spot on the arm *A* is also in contact with the wires, the circuit will be completed between the terminals and the wires will burn back to the end of the arm at *E*, usually forming a small bead. This arrangement insures uniform length of the wires between the junctions.

Care must be taken to insure insulation of the junctions from the rings, and the wires from each other except at the junctions. The wires are coated with lacquer, but care is taken to separate them as much as possible.

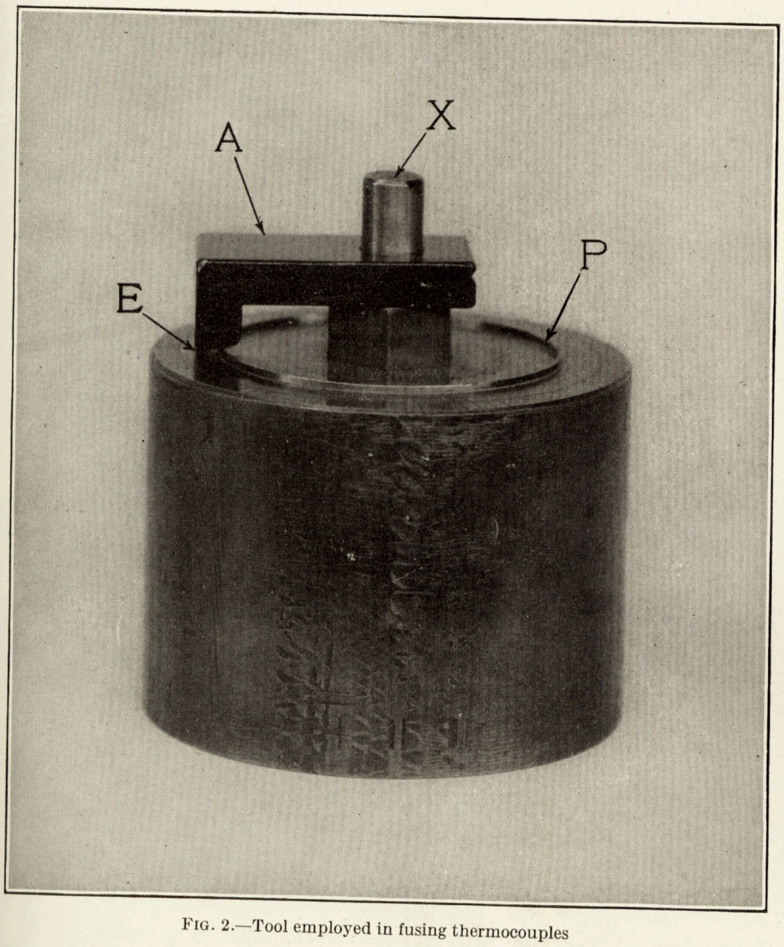

FIG. 2.—Tool employed in fusing thermocouples

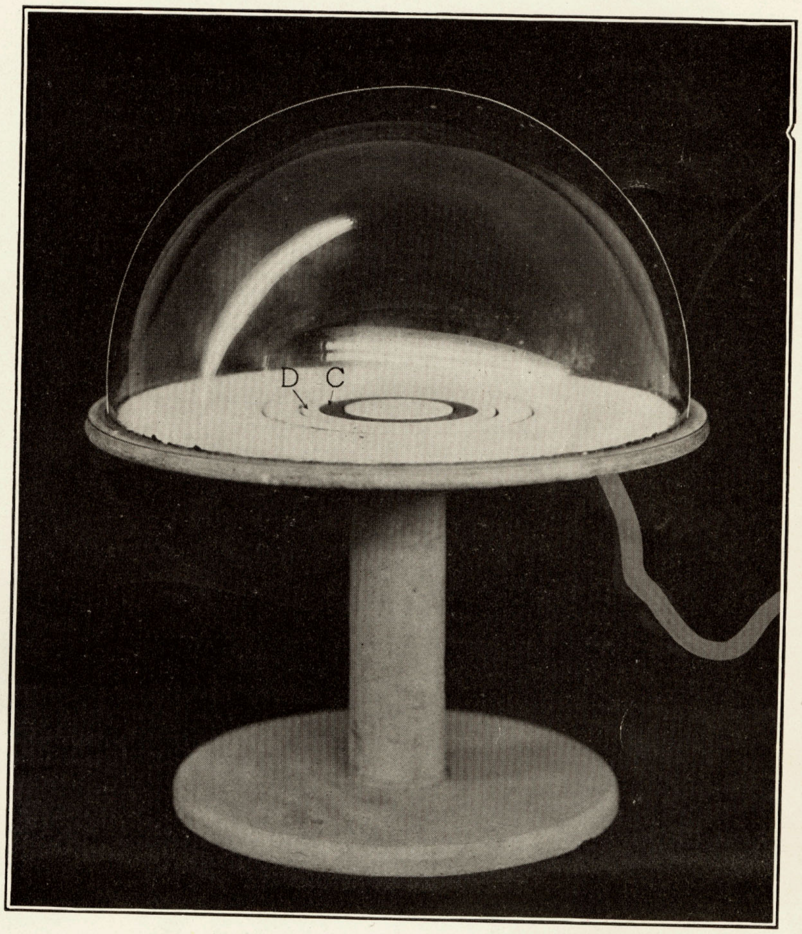

FIG. 3.—Thermoelectric pyrheliometer.

The two rings carrying the thermopile may now be mounted in a bakelite ring as shown in Figure 1, the upper surface of the inner copper ring *C* painted black, using a mixture of lampblack in alcohol, with just enough lacquer to cause the lampblack to adhere to the metal surface; and the inner disk, the outer copper ring *D*, and the upper surface of the bakelite ring painted white, using a mixture of zinc-oxide in grade 3 Zapon lacquer, or cellulose lacquer.

Through the courtesy of the Director of the Bureau of Standards, thermopile No. 3 had the upper surface of the outer ring *D* very neatly covered with a thin coating of white enamel, which was slightly thicker at the center than near the edges of the ring, giving the surface a somewhat rounded contour. Magnesium oxide produced by the combustion of magnesium shavings, was then deposited on the white enamel. After a time, and especially when exposed out of doors but under a glass cover, the magnesium oxide gradually became less white,[7] changed to a liquid, and finally dried out, leaving a hard scaly deposit like varnish.

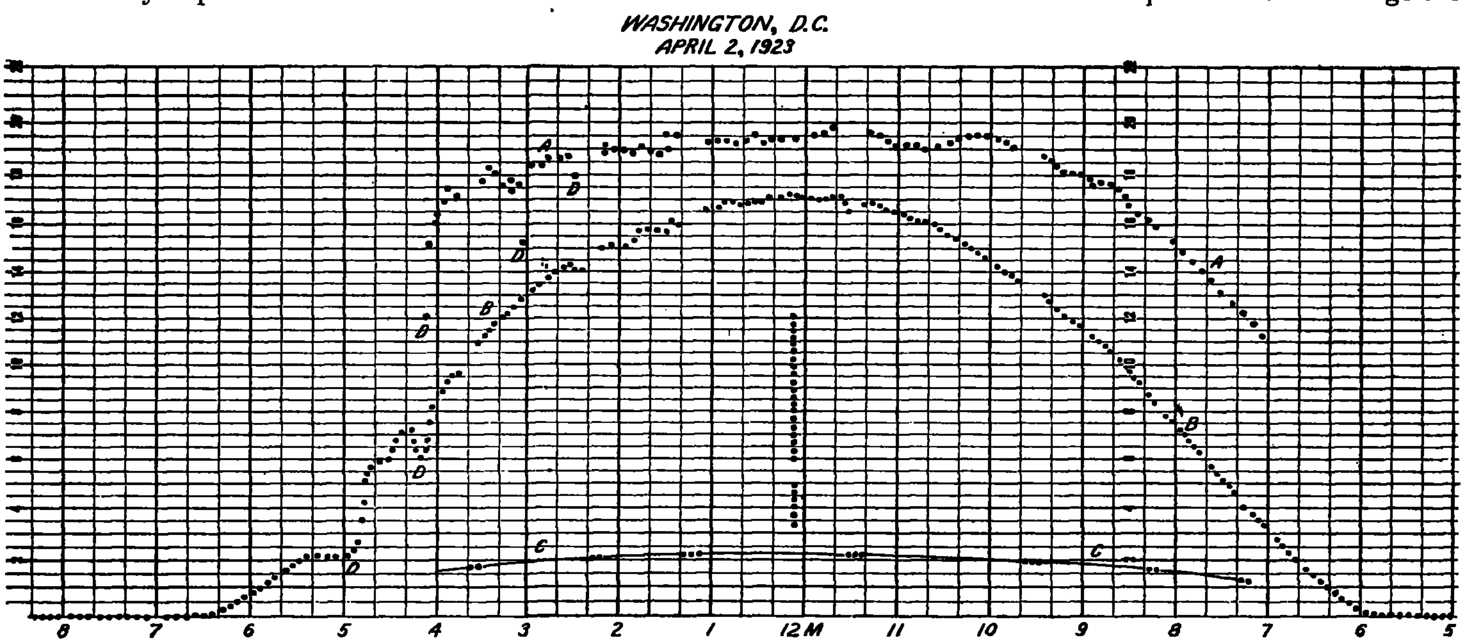

FIG. 4.—Solar radiation record.

This was the case with thermopiles Nos. 1 and 2, which were also coated with magnesium oxide. For this reason zinc oxide paint was substituted for magnesium oxide smoke, although the latter is less selectively reflective than the former. Thermopiles Nos. 4 and 5 have the zinc oxide paint applied directly to the copper surface of the ring D.

Mountings of the thermopile.—For the measurement of solar radiation the thermopile is mounted in two ways: (1) For the measurement of the intensity of direct solar radiation it is mounted in the clock-driven, equatorially mounted, diaphragmed tube designed for the Marvin pyrheliometer;[8] (2) for the measurement of the total solar and sky radiation received on a horizontal surface, the mounting is as shown in Figure 3. The thermopile in its bakelite mounting rests in an open brass box, at the top of the upright support. Surrounding this box is a brass ring, containing a groove in its upper surface, into which a glass hemisphere 4½ inches in diameter is cemented. A screw through a sleeve attached to the lower side of the brass ring secures the ring and glass cover to the support. They serve to protect the thermopile from wind and rain.

During the warm part of the year, with a sudden change from warm and moist to cool weather, or even with a change from day to night temperatures, moisture will sometimes deposit on the inside of the glass cover, which must then be removed and the moisture wiped off.

Suitable leads from the terminals of the thermopile connect with wires leading to the terminals of the register.

THE RECORDING APPARATUS.

The Weather Bureau makes use of an Engelhard type RM recording voltmeter in obtaining records of radiation intensity. At minute intervals a depressor bar presses the index arm against a record sheet under which is an inked pad, making a dot on the sheet. By using pads inked with different colors it is possible to so arrange the circuits that more than one thermopile may register on the sheet. The interval between record dots by the individual thermopiles in this case will be more than one minute.

On April 2, 1923, the upper row of dots, *A A*, Figure 4, was obtained by exposing thermopile No. 5 normally to the direct solar rays when mounted in a diaphragmed tube. The lower row of dots, *B B*, was obtained by exposing thermopile No. 4 horizontally, under a glass cover, to the total radiation from the sun and sky. Full-scale deflection represents a current intensity of 45 microamperes. The value of the scale divisions in millivolts depends upon the resistance of the thermopile, the moving coils of the voltmeter, the leads, and the swamping resistance.

For thermopile No. 5, with which the record *A A*, was obtained, the total resistance of the circuit was approximately as follows:

	Ohms.
Thermopile and leads	86
Moving coils of voltmeter	60
Swamping resistance	150
Total resistance	296

[7] Dorno (loc. cit., p. 517) refers to this same deterioration of magnesium oxide with extended exposure.
[8] See Fig. 1 Marvin pyrheliometer and auxiliary apparatus, MO. WEATHER REV., Nov., 1919, vol. 47, opp. p. 769.

Full-scale deflection on the record sheet in millivolts equals $0.045 \times 296 = 13.32$. Since there are 22 numbered divisions on the sheet, the voltage developed by the solar radiation at any time may be found by multiplying the scale reading of *A A* by 0.605.

Comparison of the curve *A A* with simultaneous readings of the Marvin pyrheliometer indicates that the solar radiation intensity in gram-calories per minute per square centimeter of surface normal to the incident solar rays may be obtained by multiplying scale readings on the curve by 0.064. A solar radiation intensity of 1 gram-calory per minute per square centimeter, therefore, develops a current having an electromotive force of 9.45 millivolts.

For thermopile No. 4, with which the record *B B* was obtained, the total resistance of the circuit was approximately as follows:

	Ohms.
Thermopile and leads	83
Moving coils of voltmeter	60
Swamping resistance	200
Total resistance	343

Full-scale deflection on the record sheet in millivolts equals $0.045 \times 343 = 15.44$, and the voltage developed by the radiation may be found by multiplying the scale reading of *B B* by 0.70.

Comparison between the readings of the Marvin pyrheliometer and *B B*, Figure 4, is effected by shading the rings *C* and *D*, Figure 3, from direct sunshine at intervals throughout the day, and drawing a smooth curve *C C*, Figure 4, through the records of diffuse sky radiation thus obtained. The number of scale divisions between *B B* and *C C*, at any time, is a measure of the intensity of the vertical component of direct solar radiation, or its intensity on a horizontal surface, at that time, and may be compared with the vertical component of synchronous readings of the Marvin pyrheliometer.

Such comparisons indicate that for curve *B B* the radiation intensity in gram-calories per minute per square centimeter may be obtained by multiplying the scale readings of the curve by 0.073. A solar radiation intensity of 1 gram-calory per minute per square centimeter, therefore, develops a current having an electromotive force of 9.6 millivolts.

It will be noted that at noon of April 2 the sky radiation (2.3 scale divisions on the record sheet) was about 13.5 per cent of the total radiation received on a horizontal surface (17.0 scale divisions).

From the data given above we may compute that shortly before noon on April 2 the blackened ring *C* of thermopile No. 5 was receiving solar radiation at the rate of 1.30 gram-calories per minute per square centimeter, or 4.77 gram-calories per minute upon the 3.67 square centimeters of its surface. Reduced to units of work, this equals 0.33 watts per second.

The current generated by the thermopile was about 40.7 microamperes, with an E. M. F. of 12.05 millivolts, which equals 0.00000049 watts, or about 0.0000015 of the heat energy received by the blackened ring.

On Figure 4, the depressions marked *D* on curves *A A* and *B B* show the effects of passing bands of cirrus clouds.

The vertical row of dots just after the 12 m. time line were made at 12, noon, apparent time.

Accuracy of the record.—Records obtained by means of thermoelectric pyrheliometers are subject to the following errors:

(1) As shown by the Bureau of Standards tests, the E. M. F. generated is not strictly proportional to the difference between the temperature of the junctions attached to the black and the white rings, respectively. The efficiency of the thermopile appears to increase with temperature difference, and presumably with the temperature of the pile.

(2) The resistance of all the wires except that in the swamping resistance increases with temperature, but at a slower rate than the E. M. F. increases.

(3) It is not probable that the difference in the temperature of the junctions attached to the black and the white rings, respectively, is strictly proportional to the intensity of the radiation to which they are exposed.

(4) The hemispherical glass cover over the horizontally exposed thermopile may cause irregularities in the record unless it is exactly spherical, is free from flaws of all kinds, and is large enough so that the caustic curve caused by the reflection of light from its internal surface does not fall on either of the rings.

On account of the small diameter of these rings (outer diameter of the white ring equals 1.52 inches), the requirement that the diameter of the glass cover should be more than double the diameter of the ring[9] has been more than met in providing a cover 4.5 inches in diameter. The covers are not entirely free from waves and other defects, however.

It remains to investigate the combined effect of (1), (2), (3), and (4).

The comparisons of curve *A A*, Figure 4, for thermopile No. 5, with the readings of a Marvin pyrheliometer are given in Table 1, where each value given is the mean of from three to nine readings.

TABLE 1.—*Comparison of thermopile No. 5, with Marvin pyrheliometer No. 3.*

Hour angle of sun.	Marvin pyrheliometer.	Thermopile No. 5 scale reading.	Pyrheliometer / Thermopile.
	Gr.-cal.		
4:59 a. m	0.729	11.5	0.0634
4:38 a. m	0.816	13.0	0.0628
4:05 a. m	0.979	15.1	0.0648
3:28 a. m	1.091	17.2	0.0634
2:20 a. m	1.222	19.2	0.0636
0:20 a. m	1.309	19.7	0.0664
2:32 p. m	1.194	18.7	0.0638
3:44 p. m	1.074	17.2	0.0624
Mean			0.0638

A slight tendency is noted for the thermopile to read relatively low in the middle of the day.

Curve *B B*, for thermopile No. 4, exposed horizontally under a glass cover, when compared with the vertical component of the readings of the Marvin pyrheliometer, shows some distortion of the record due to imperfections in the glass cover. For example, between 2 p. m. and 4 p. m., apparent local time, curve *B B* is relatively higher than between 8 a. m. and 10 a. m. This distortion disappeared in later records when a better glass cover was used.

It is possible that an annual variation may be found in the ratio Marvin pyrheliometer/Thermopile. Further use of the thermopiles is necessary to answer this question.

Also, it has not yet been demonstrated how well the white paint used on the ring *D* will withstand sunlight.

The authors believe, however, that the thermoelectric pyrheliometer will prove a reliable and useful instrument.

[9] Miller, Eric R., Internal reflection as a cause of error in the Callendar bolometric sunshine receiver. *Monthly Weather Review, 43: 264–266*