RADIATION THERMOPILE DESIGN

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ABSTRACT

Previous formulas for the design of radiation thermopiles to be used with a Thomson galvanometer are summarized and new formulas for the design of thermopiles for use with D'Arsonval galvanometers are developed.

A design of thermopile is described in which the cold junctions almost entirely surround the hot junctions thus reducing drifts. In this design, each element is constructed as a separate unit and when all are completed they are simply stacked up and fastened together with one screw, thereby minimizing the danger of breakage. The whole thermopile fits into a cubical evacuated case only 10 mm on an edge and, being so small, it can be used directly in front of an elliptical mirror which forms a small hot image, in some cases increasing the deflection due to a given radiation by a factor of 3. By a slight modification of the spectrometer, a thermopile having adjustable compensation can be utilized which, theoretically, will give almost no drifts due to changes in temperature of the optical parts of the spectrometer or of the surroundings.

A convenient technique of construction is described.

In constructing a radiation thermopile, such as might be used on an infrared spectrograph, one hopes to achieve an instrument which, for a given radiation, will produce a maximum deflection of the available galvanometer, will respond in a minimum time, will give a steady zero and freedom from drift, and will be easy to build. To attain these results one is free to choose such factors as the material, length and diameter of the wires, the number of junctions, the design of the mounting, etc. This paper deals with the theoretical and practical choice of the design which will most nearly approximate the ideal when the limitations of available materials are considered.

A complete theoretical treatment of the design of vacuum thermopiles for use with the Thomson galvanometer is given by Johansen (Annalen der Physik, *33*, p. 517, complete discussion of design of uncompensated type; Physikalische Zeitschrift *14*, p. 998, application of previous results to design of compensated type.) Since the advent of the Moll relay for amplifying galvanometer deflections, (Phil. Mag. 50, p. 624, 1925) thermopiles are more often connected to a D'Arsonval galvanometer than to the Thomson type. Since the sensitivity of these two types of galvanometer varies in a different way as the circuit resistance is varied, the design of the most sensitive thermopile for use with them is different. For instance, the best thermopile for use with the Thomson galvanometer has a resistance equal to that of the galvanometer, while the best thermopile for use with a D'Arsonval type having an adjustable magnetic shunt for critical damping, has a resistance several times the galvanometer resistance. The theory developed here follows the general method of Johansen but applies to the design for use with a moving coil galvanometer.

DESIGN FOR GREATEST SENSITIVITY

Suppose that a thermopile is to be designed suitable for use with a D'Arsonval galvanometer of resistance G, and having an adjustable magnetic shunt for securing critical damping. Let the total receiving area which the thermopile must have in order to intercept all the radiation which is delivered to it by the spectrograph be denoted by A; this would approximately equal the area of the exit slit of the spectrograph. Suppose that the thermopile is to be built by a series combination of a number N of the uncompensated type of element shown as Type 1, Fig. 1. In this type of element, the fine thermoelectric wires are soldered together and the free ends then soldered to comparatively massive copper supports to which the connections are made. To the junction of the fine wires is also soldered a blackened metal receiving area which serves to absorb radiation and conduct heat to the junction. Unfortunately, when the receiving area is warmed by the absorbed radiation, it loses energy at a certain rate by re-radiation; it also loses energy by conduction of heat along the wires. It is assumed that the thermopile container is evacuated so that heat loss by conduction to

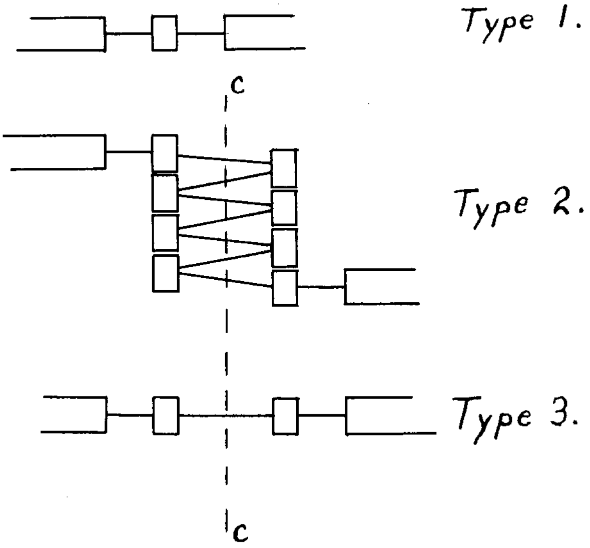

FIG. 1.

the air is negligible; however, since both the radiation and air conduction losses are, for such small temperature differences, proportional to the area of the receiver and to the temperature difference, the same theory applies to thermopiles in air or in vacuum provided that a suitable value of radiation constant is chosen. If these losses are computed and placed equal to the rate at which radiant energy is absorbed, the deflection of the galvanometer can be found.

Theoretically, the sensitivity, measured in millimeters per open circuit microvolt, of a D'Arsonval galvanometer having an adjustable magnetic shunt which is always adjusted to give critical damping, is inversely proportional to the square root of the total circuit resistance.

$$S_v = \frac{g}{\sqrt{G+R}} \text{ millimeters per open circuit microvolt}$$

where g is a sensitivity constant of the galvanometer, G its resistance, and R the resistance of the thermopile. Several Kipp and Zonen, Type Z galvanometers were tested and found to obey this law with sufficient accuracy.

The open circuit voltage generated by a thermopile of N elements, each having a temperature difference of t degrees and thermoelectric power E microvolts per degree is

$$e = NEt.$$

The rate of loss of heat per element by conduction along the wires is $t(c_1s_1+c_2s_2)$ where c_1, c_2 are the heat conductivity coefficients of the materials of the wires and s_1, s_2 are cross sectional area of a wire divided by its length. The rate of loss of heat by re-radiation is per element, AOt/N where O is a radiation constant. If the receiver were perfectly black on both sides O would be 3.0×10^{-4} calories per square centimeter per second per degree but the blackened side radiates about 0.9 as well as a black body and the unblackened side about 0.1 as well so that a good value for O under such circumstances is 1.5×10^{-4}. The resistance of the thermopile is $N/k_1s_1+N/k_2s_2$ where k_1, k_2 are the electrical conductivities. If a radiation of surface density W calories per square centimeter per second falls on this thermopile the energy absorbed per element will be WAB/N, where B is the absorption coefficient of the receiver for the radiation falling on it. Placing this rate of absorption of energy equal to the rate of loss by radiation and conduction, an expression for t can be found which, when placed in the equations preceding, yields the result that the deflection of the galvanometer

$$D = \frac{g}{\sqrt{G + \dfrac{N}{k_1 s_1} + \dfrac{N}{k_2 s_2}}} \, \frac{WBAE}{\left(\dfrac{AO}{N} + c_1 s_1 + c_2 s_2\right)}.$$

N, s_1, and s_2 are now to be so chosen as to make the deflection a maximum. On solving for a maximum we find that the larger N is, the larger D will be, although the gain is slight after a certain value of N is reached. The best value of s_1 for a given value of N is

$$s_1 = \frac{-Nc_1\left(1 + \sqrt{\dfrac{k_1 c_2}{k_2 c_1}}\right) + \sqrt{\left[Nc_1\left(1 + \sqrt{\dfrac{k_1 c_2}{k_2 c_1}}\right)\right]^2 + 8k_1 c_1 AOG}}{4k_1 c_1 G}$$

and the best value of s_2 is

$$s_2 = s_1 \sqrt{\frac{k_1 c_1}{k_2 c_2}}.$$

In designing, various practical values of N are chosen and the corresponding values of s_1, s_2 and D computed from the above formulas. A compromise is then made between one's desire for large deflections and one's ambition for constructing many elements.

It sometimes happens that the electrical and heat conductivity coefficients of the materials of the wires are not known. In this event a good design may still be achieved by assuming a value for the ratio of the electrical conductivity to the heat conductivity $k_1/c_1 = k_2/c_2 \equiv b = 6 \times 10^5$; this value will, in most cases, be sufficiently accurate. The above equation for the best value of s_1 may now be used to find $1/k_1 s_1 = 1/k_2 s_2 = r$, the best resistance of one wire;

$$r = \frac{2G}{-N + \sqrt{N^2 + 2bAOG}}.$$

The resistance of the available wire per unit length may easily be measured and pieces cut of such length as to give the resistance required by the above equation. A check on the proper design of the completed element may be made by measuring its resistance, which should be $2r$. The deflection given by any pile now reduces to

$$D = \frac{g}{\sqrt{G + 2Nr}} \, \frac{WBAE}{\left(\dfrac{AO}{N} + \dfrac{2}{rb}\right)}$$

and for large values of N the deflection of the best design of pile is

$$D = \frac{gBEWA}{4}\sqrt{\frac{b}{AO}}.$$

In this last equation, WA is the total amount of radiation falling on the thermopile. It is thus seen that the deflection produced by a given amount of radiation is inversely proportional to the square root of the total area; it is therefore an advantage to use, near the emergent slit of a spectrograph, a concave mirror which will form a small image of the emergent slit, the thermopile then being constructed to fit this reduced image.

Similar design formulas were worked out for the case where the D'Arsonval galvanometer does not have an adjustable magnetic shunt, but requires a certain resistance in the thermopile to secure critical damping. These formulas are given on pp 640. The best design of thermopile to have a given resistance, has a finite number of elements; this number may be determined by the formula given.

DESIGN OF COMPENSATED TYPES

The design of Types 2 and 3, Fig. 1, can be derived from the design of Type 1 in a manner explained below. In Types 2 and 3 an extra set of junctions is provided which are shielded from the radiation to be measured, the purpose of these compensating junctions being to minimize drifts. The addition of the extra set of junctions decreases the sensitivity of the thermopile, both because of the increase in resistance and because of the back emf generated by the compensating junctions due to the heat which they receive by conduction from the hot junctions. Johansen has shown that, both of these effects considered, the wire joining two receivers in the Type 2 should have twice the resistance of one of the wires joining the receiver of Type 1 to the support. One may consider the centerline *cc* of Fig. 1 as the dividing line between the junctions, and may consider that one junction consists of a receiving area with that portion of the two wires which reach from it to the centerline (or a support). With this convention, a junction of a thermopile of Type 2 should be the same as a junction of a Type 1 thermopile which was designed to cover the total area covered by both sets of junctions, and to have the same total number of junctions. For example, if we wish to design a Type 2 pile having receiving junctions covering an area of 0.1 cm^2 and having compensating junctions of this same area, we would design a Type 1 pile to cover an area of 0.2 cm^2. This Type 1 design would call for N junctions in order to attain good sensitivity. Half of these junctions would be used for receiving the radiation and the other half connected in series opposition for compensation. Of course, in actual construction, one continuous piece of wire of twice the resistance of a Type 1 junction wire, reaches from a receiving junction to a compensating junction.

Although the argument of Johansen concerning the relation of Type 2 and Type 1 piles does not apply to Type 3, the author has worked out the design of Type 3 and finds the same result as Johansen found for Type 2. Type 3 may therefore be considered as a series opposing connection of a two junction Type 1 pile. Type 1 is about 40% more sensitive than Types 2 and 3.

TIME OF RESPONSE

It is important that the time of response should be a minimum, both for conserving time in the taking of readings and for minimizing the effects of drifts on the readings. The time of response depends on the heat capacity of the various parts which are warmed, on the rate of loss of heat, and on the time required for heat to travel along the warmed parts.

In considering the design to give the largest deflection for a given radiation, we found a formula for the best resistance of the thermopile wires, but there was no additional condition stating whether this resistance was to be realized by a long wire of large diameter or by a short fine wire. By consideration of both the heat capacity of the wire and the time required for a thermal disturbance to travel along it, we see that the short fine wire should be used. One therefore chooses as fine a wire as can be conveniently handled and soldered, and cuts it to such a length as will give the required resistance. If the resistance of the wire is made somewhat less than the value which gives greatest deflections, the loss of heat by conduction along the wire will be greater and the time of response will therefore be shorter. Computation shows that as the resistance of the wire is decreased from its value for largest deflection, the time of response decreases at first, more rapidly than the deflection decreases (see pp. 642); consequently, it is an advantage to cut the wires to about 60% of the length computed for largest deflection. It is sometimes said that the Hutchins alloys of bismuth-tin and bismuth-antimony (American Journal of Science, Vol. *48*, p. 226, 1894), have such a high specific resistance that even though their thermoelectric power is high, it is no advantage to use them. But from our formulas for the deflection of a properly designed pile we see that if the ratio of the electrical conductivity to the heat conductivity is the same as for most other metals, then the deflections are independent of the specific resistance of the material of the wires. In fact, from the standpoint of the time of response, it is an advantage to have a moderately high specific resistance, because a very short wire of comfortable diameter for soldering may be used and still have the proper resistance for good deflections; in this case the heat capacity of the wire will be small and a thermal disturbance will travel along it in a minimum time.

For quick response, the blackened metal receiving area should be thin and have good heat conductivity associated with a minimum heat capacity. Johansen has pointed out that if the receiver is made too thin, then its heat conductivity will be so reduced that there will be a considerable temperature drop along the receiver as heat is conducted toward the thermal junction at its center. As a consequence, a given amount of radiation falling near the end of a receiver will produce a smaller deflection than if it fell on the center. According to Johansen the ratio of these two deflections would be

$$\frac{\textit{Deflection with radiation falling at center}}{\textit{Deflection with radiation falling } L \textit{ cm from center}} = \cosh L\sqrt{\frac{O}{cd}}$$

where c is the heat conductivity, O the radiation constant and d the thickness in centimeters. If we agree to permit this ratio to be as large as 1.25, then for a tin receiver of thickness 0.001 mm the distance from center to edge of the junction may be as great as 2.1 mm, and for a silver receiver, 5.4 mm. Thus, from this standpoint, a receiver not more than 4 mm diameter may be made as thin as 0.001 mm without serious loss of efficiency, which is about as thin as will give sufficient mechanical strength. For quick response the receiver should be smaller than 4 mm diameter in order that heat may flow across it quickly and establish thermal equilibrium.

The heat capacities of the metal receivers, of the blackening, and of the wires may be computed and by comparing their magnitudes one may estimate the advantage of reducing the heat capacity of any one of them. For instance, the first thermopile constructed by the author had a tin receiver 4 mu thick, the wire had a heat capacity equivalent to 2 mu of tin, and the thinnest coating of lamp black which was possible to apply had a heat capacity equivalent to 6 mu of tin. When evacuated the time required to reach the full deflection was 12 sec.

There would obviously be but small advantage in using finer wires as the heat capacity is in the lamp black coating. A later design was blackened with Aquadag which could be applied in a thinner coat and had a heat capacity equivalent to 1 mu of tin. This thermopile gave the full deflection in 6.5 seconds. While most of the deflection was reached in 2 sec. it was the full 6.5 sec. before the movement of the galvanometer became imperceptible.

EVACUATION FACTOR

A receiver which is perfectly black on one side only, loses roughly 11 times as much heat by conduction into the air at atmospheric pressure as by radiation. If the loss by wire conduction were equal to the loss by radiation, then the sensitivity in air would be 1/6 the sensitivity in vacuum. The factor which is shown by most properly constructed thermopiles is about 1/8. A factor such as 1/40, which is sometimes reported, arises when the receivers are not blackened and the wire conduction losses are correspondingly small; it does not indicate an exceptionally good sensitivity in vacuum, but rather an exceptionally low sensitivity in air. If the factor is only 1/2 it indicates that the wire conduction losses are unduly large.

A thermopile may be designed for use in air by using a value of *O*, 12 times as large as for vacuum. Since the sensitivity of the best thermopile varies inversely as the square root of *O*, the sensitivity of the best vacuum thermopile is 3.5 times the sensitivity of the best thermopile in air. However, the best thermopile in air would be more laborious to construct as it would have many more elements.

SUMMARY OF DESIGN FORMULAS

Below is given a summary of formulas for the number of elements and the resistances of the wires to give the largest deflection from a given radiation. Separate formulas are given for the design for use with a Thomson galvanometer, a D'Arsonval galvanometer requiring a certain external resistance for critical damping, and a D'Arsonval galvanometer with adjustable magnetic shunt. These formulas are for a Type 1 pile and can be applied to the design of Types 2 and 3 as explained above. All formulas are given both in the exact form and in the approximate form which assumes a certain value for the ratio of the electrical and heat conductivities.

In designing a thermopile for use with the Thomson galvanometer the number of elements and the resistances of the wires are simply computed from the formulas given. The effect on the deflection, of any departure from this best design may be computed from the expression for D. This formula was derived on the assumption that the sensitivity of the Thompson galvanometer in mm per microampere is $g\sqrt{G}$.

In a similar way one may design a thermopile for use with a D'Arsonval galvanometer requiring a certain resistance in the thermopile in order to obtain critical damping. By making a little computation from the expression for D, it can be shown that the deflection will be largest if the galvanometer has been so designed as to require an external critical damping resistance which is several times the resistance of the galvanometer. If the external damping resistance which the galvanometer requires is equal to the resistance of the galvanometer, then the best thermopile built to meet this condition will give only 68% as much deflection as if the thermopile has been built to have 6 times the resistance of the same galvanometer, the magnetic field of the latter having been increased so as to give critical damping with this larger external resistance. Therefore, in ordering a new galvanometer it is an advantage to specify an external critical damping resistance several times as large as the galvanometer resistance. Having met this condition, the resistance of the galvanometer is not important from the standpoint of deflection, except that if the resistance is too small, then the connections to the coil have an appreciable part of the total resistance and thereby decrease the efficiency. If the galvanometer resistance is too large, a thermopile of large resistance must be constructed and this means a large number of junctions and much labor. 10 or 15 ohms is a good value for the galvanometer resistance.

If one wishes to design a pile for use with a D'Arsonval galvanometer having an adjustable magnetic shunt one must remember that the larger the number of elements N, the larger will be the deflection. Certain practical values of N are assumed and the corresponding deflections computed; a value of N is then chosen as a compromise between deflection and labor of building.

In any design, the resistance of the wires may be chosen somewhat smaller than the value for largest deflection in order to decrease the time of response, as explained in the next section.

LIST OF SYMBOLS

A, total area which is to be covered by the receivers in cm^2.

O, radiation constant, 1.5×10^{-4} cal/sec cm^2 degree if receiver is thoroughly black on one side only.

G, galvanometer resistance, ohms.

g, a galvanometer sensitivity constant.

N, number of elements.
r_1, r_2, resistances of single wires.
k_1, k_2 electrical conductivities, mho/cm^3.
c_1, c_2, heat conductivities, cal/cm^3 sec.
b, ratio of electrical conductivity to heat conductivity, 6×10^5 for most metals.
W, surface density of received radiation, cal/cm^2 sec.
B, absorption coefficient of receiver for incoming radiation.
E, thermoelectric power of the wires, microvolts/degree.
X, thermopile resistance, ohms.

Best design of thermopile for use with Thomson galvanometer of resistance G.

Exact formulas

$$N = \frac{\sqrt{GAO}}{\sqrt{\dfrac{c_1}{k_1}} + \sqrt{\dfrac{c_2}{k_2}}}$$

$$r_1 = \frac{Nc_1\left(1 + \sqrt{\dfrac{k_1c_2}{k_2c_1}}\right)}{k_1AO}$$

$$r_2 = r_1\sqrt{\frac{k_1c_2}{k_2c_1}}.$$

Deflection produced by thermopile of best design

$$D = \frac{gWBE}{4\sqrt{O}}\,\frac{\sqrt{A}}{\sqrt{\dfrac{c_1}{k_1}} + \sqrt{\dfrac{c_2}{k_2}}}.$$

Deflection produced by thermopile of any design

$$D = \frac{gWBE\sqrt{G}}{(G + Nr_1 + Nr_2)} \cdot \frac{A}{\left(\dfrac{AO}{N} + \dfrac{c_1}{k_1r_1} + \dfrac{c_2}{k_2r_2}\right)}$$

$$X = Nr_1 + Nr_2.$$

Approximate formulas assuming $k/c = b = 6\times 10^5$

$$N = \frac{\sqrt{GAOb}}{2}$$

$$r_1 = \frac{2N}{AOb}$$

$$r_2 = r_1.$$

Deflection produced by thermopile of best design

$$D = \frac{gWBE\sqrt{bA}}{8\sqrt{O}}.$$

Deflection produced by thermopile of any design

$$D = \frac{gWBE}{G + 2Nr_1}\,\frac{A}{\left(\dfrac{AO}{N} + \dfrac{2}{br_1}\right)}$$

$$X = 2Nr_1.$$

Best design of thermopile for use with D'Arsonval galvanometer requiring X ohms for critical damping.

Exact formulas

$$N = \frac{\sqrt{XAO}}{\sqrt{\dfrac{c_1}{k_1}} + \sqrt{\dfrac{c_2}{k_2}}}$$

$$r_1 = \frac{X}{N\left(1 + \sqrt{\dfrac{k_1 c_2}{k_2 c_1}}\right)}$$

$$r_2 = r_1 \sqrt{\frac{k_1 c_2}{k_2 c_1}}.$$

Deflection given by this thermopile of resistance X

$$D = \frac{gWBE}{\sqrt{G+X}} \frac{A}{\left(\dfrac{AO}{N} + \dfrac{c_1}{k_1 r_1} + \dfrac{c_2}{k_2 r_2}\right)}$$

Approximate formulas assuming $k/c = b = 6 \times 10^5$.

$$N = \frac{\sqrt{XAOb}}{2}$$

$$r_1 = \frac{X}{2N}$$

$$r_2 = r_1.$$

Deflection given by this thermopile of resistance X

$$D = \frac{gWBE}{\sqrt{G+X}} \frac{A}{\left(\dfrac{AO}{N} + \dfrac{2}{br_1}\right)}.$$

Best design of thermopile for use with D'Arsonval galvanometer having adjustable magnetic shunt for securing critical damping.

Exact formulas

D increases as N increases although the gain is slight after a certain value of N is reached. Assume values of N and compute D. Then select a practical N for construction.

$$r_1 = \frac{4G}{-N\left(1+\sqrt{\dfrac{k_1 c_2}{k_2 c_1}}\right) + \sqrt{\left[N\left(1 + \sqrt{\dfrac{k_1 c_2}{k_2 c_1}}\right)\right]^2 + 8\dfrac{k_1}{c_1}AOG}}$$

Approximate formulas assuming $k/c = b = 6 \times 10^5$.

(See remark opposite)

$$r_1 = \frac{2G}{-N + \sqrt{N^2 + 2bAOG}}$$

$$r_2 = r_1\sqrt{\frac{k_1c_2}{k_2c_1}}.$$

For very large values of N

$$r_1 = \frac{Nc_1\left(1 + \sqrt{\frac{k_1c_2}{k_2c_1}}\right)}{k_1AO}.$$

The deflection given by any thermopile is

$$D = \frac{gWBE}{\sqrt{G + Nr_1 + Nr_2}} \cdot \frac{A}{\left(\frac{AO}{N} + \frac{c_1}{k_1r_1} + \frac{c_2}{k_2r_2}\right)}$$

$$X = Nr_1 + Nr_2.$$

$$r_2 = r_1.$$

For very large values of N

$$r_1 = \frac{2N}{bAO}.$$

The deflection given by any thermopile is

$$D = \frac{gWBE}{\sqrt{G + 2Nr_1}} \cdot \frac{A}{\left(\frac{AO}{N} + \frac{2}{br_1}\right)}.$$

For large values of N, the deflection given by the best thermopile is independent of G and is

$$D = \frac{gBEWA}{4}\sqrt{\frac{b}{AO}}$$

$$X = 2Nr_1.$$

EXAMPLE

Suppose that a Type 1 thermopile of total receiving area of 0.06 cm^2 is to be designed for use with a galvanometer of 18 ohms resistance and having an adjustable magnetic shunt for securing critical damping. If we assume the usual value for the ratio of the electrical conductivity to the heat conductivity, and use the approximate formulas, then the best resistances of the wires will be independent of the material used. We assume N and compute the corresponding values for r_1 and D, the values being tabulated on pp. 642.

From this computation we see that a three element thermopile will have about 63% of the ideal sensitivity and a five element thermopile, 77%. In the formula for D, the radiation loss per element per degree is the expression AO/N and the conduction loss is $2/br_1$. These losses have been tabulated above and one sees that for a properly constructed

N	r_1 ohms	$\left[\frac{D}{gWAEB}\right]$ Proportional to deflection	X ohms	Losses per element per degree cal/sec		
				By Radiation	By Conduction	
1	2.77	2.02×10^4	5.55	9.0×10^{-6}	1.2×10^{-6}	Best values
3	3.22	4.06	19.3	3.0	1.03	
5	3.68	4.98	36.8	1.80	.907	
10	5.05	5.90	101.	.90	.655	
100	37.0	6.45	7400.	.090	.090	

For deviations from best values of r_1						% Deflection	% Time
3	3.22	4.06	19.3	3.0	1.03	100	100
3	1.61	3.86	9.6	3.0	2.06	95	80
3	1.07	3.33	6.43	3.0	3.09	82	66
3	.64	2.62	3.86	3.0	5.15	64	49

thermopile with a large number of elements the loss by radiation is equal to the loss of conduction; for a small number of elements the loss by radiation is considerably greater than the loss by conduction. In the lower part of the table a computation is made assuming that for a three element thermopile, r_1 is made smaller than the best value as given by the formula. The computations show that the deflection is not very sensitive to small changes in r_1 from its best value, in fact the deflection drops only 5% when r_1 is made one half of its best value. When r_1 is made smaller the rate of loss of heat by conduction increases and the time of response may be assumed to be inversely proportional to the sum of the rates of loss of heat by radiation and conduction. On this assumption, two additional columns have been computed showing the percentage decrease in time of response and deflection due to a decrease in r_1. From this it is seen that the time of response decreases more rapidly at first than the deflection, consequently it is an advantage to cut the wires to about half the length indicated by the formula and thereby have r_1 be half as great. How much shorter to cut the wires depends on the relative importance of deflection and time of response.

DRIFTS

Drifts are caused by a continuous change in the temperature difference of the hot and cold junctions of a thermopile. They may be caused by conduction of heat to and from the thermopile case, producing a temperature change of hot and cold junctions at different rates, or by the heating or cooling of some neighboring part which can interchange radiation with the junctions. Sometimes the window of a vacuum thermopile absorbs some radiation and then re-radiates it slowly to the receivers, thus producing a drift. Air currents are also a source of trouble but can be eliminated by evacuation. In order to reduce drifts it is customary to build a Type 2 thermopile, which is so placed that the spectral lines can fall on only one set of junctions, the other set being covered by a shield so as not to be affected by the spectrum. If the two sets of junctions have equal sensitivity, the thermopile will be fairly well compensated against changes of radiation from the rear; but if any of the optical or other parts of the spectrograph which are in front of the thermopile should change in temperature, only the one set of junctions is affected and a drift will result. The author believes that an uncompensated Type 1 thermopile in which a massive cold junction entirely surrounds the hot junction except for a hole through which the radiation comes, will give no worse drifts than the Type 2, and will be 40% more sensitive.

Whereas drifts are usually blamed on the thermopile, they are more often caused by temperature variations of other parts of the spectrometer. It is very useful to have the spectrometer heat insulated so that any temperature variations are slow and uniformly distributed.

DESIGN OF THE MOUNTING

Fig. 2 shows a method of constructing a Type 1 thermopile in which the cold junctions almost entirely surround the hot junctions. It is usually difficult to construct a thermopile of many elements because of the danger of breaking the first junctions built, while constructing the last. In this design, each element is constructed as a separate unit and when all are completed they are simply stacked up and fastened together with one screw. Each element consists of two horseshoe shaped copper pieces 1, which are insulated from each other by a thin mica separator of the same shape. The combination is held together by Duco lacquer painted around the edge. A #40 copper wire 2 is soldered in a groove cut in each copper block, and to the ends of these copper wires are soldered the thermoelectric wires which hold the receiver at the center. The #40 copper wires are used as it is much easier to solder the thermoelectric wires to them than to the copper blocks, and by bending the wires, the receiver may be brought to the desired place.

The conduction of these copper wires is so good that they may in effect be considered as part of the copper block. As many of these elements as desired are assembled with the necessary end plates and connection blocks and held together with one screw. This automatically makes the series connection of the elements. The receivers are built at the center of the hole in the copper blocks and the hole is nickeled and polished so that a certain amount of the heat loss by radiation from the receiver is returned to it; also if the incoming radiation should miss the receivers slightly or pass between them, it will be returned to the back of the receivers. The copper blocks are compactly built and the case fits them closely, the whole thermopile being contained in a cubical box about 10 mm on an edge. Since this thermopile has so many metal parts, it is necessary to have a vacuum pump available at all times, but a good oil pump will do as the vacuum need be only 0.001 mm. Being so small it may, without appreciable loss of energy, be placed in front of a mirror which will form a condensed image of the exit slit of the spectrograph on the junctions. By using an elliptical mirror one may condense the image to such a size that a thermopile built to receive this small image will give 3 times the deflection of a thermopile built to receive the full sized image at the exit slit.

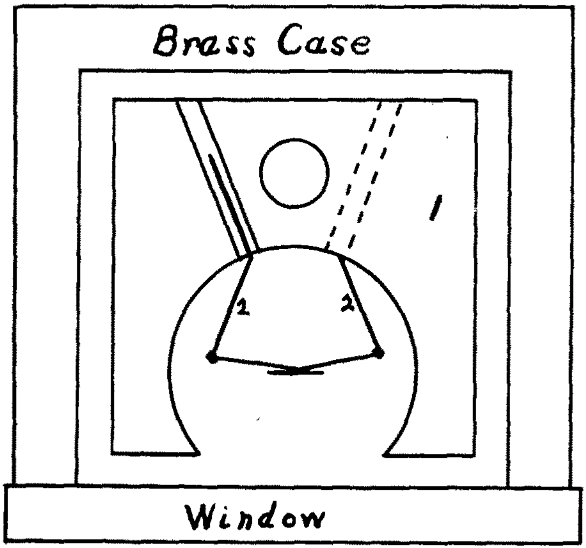

FIG. 2.

By a slight modification of the spectrometer it is possible to build a thermopile which is theoretically quite free from drifts due to changes in the temperature of the parts of the spectrograph. The theory of this method of compensation is simply that a set of compensating elements should, as far as possible, "see" the same parts of the spectrograph as the regular elements. The exit slit of the spectrometer is modified as shown in Fig. 3 by the addition of extra lengths of slit 3, both above and below the regular slit, the width of these compensating slits being adjustable independent of the regular slit. An image of this modified exit slit is then focused on a thermopile of the form shown in Fig. 4. This is built of the kind of elements shown in Fig. 2 and has three regular elements in the center which receive the image of the regular exit slit, and has compensating elements above and below which receive the images of the compensating slits. The compensating elements are connected in series with the circuit so that their voltage is opposed to the voltage of the regular junctions. The combined area of the two compensating receivers is somewhat greater than the total

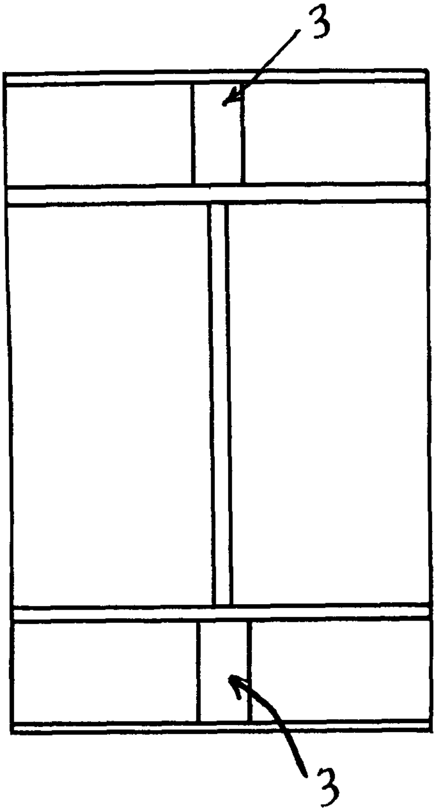

Fig. 3.

area of the regular receivers so that if a diffuse radiation falls on the whole thermopile, the compensating elements will generate more voltage than the regular elements. An extra connection is brought out from the thermopile so that a copper resistance coil can be shunted across the compensating elements, this resistance being adjusted to such a value that when a small lamp is flashed on and off at a certain distance in front of the thermopile, no deflection is produced. Having set the width of the regular exit slit, the width of the compensating slits is now adjusted till the flashing of a lamp placed in front of the grating or prism, produces no deflection. If now the temperature of the mirrors or of the grating should change continously, the change of

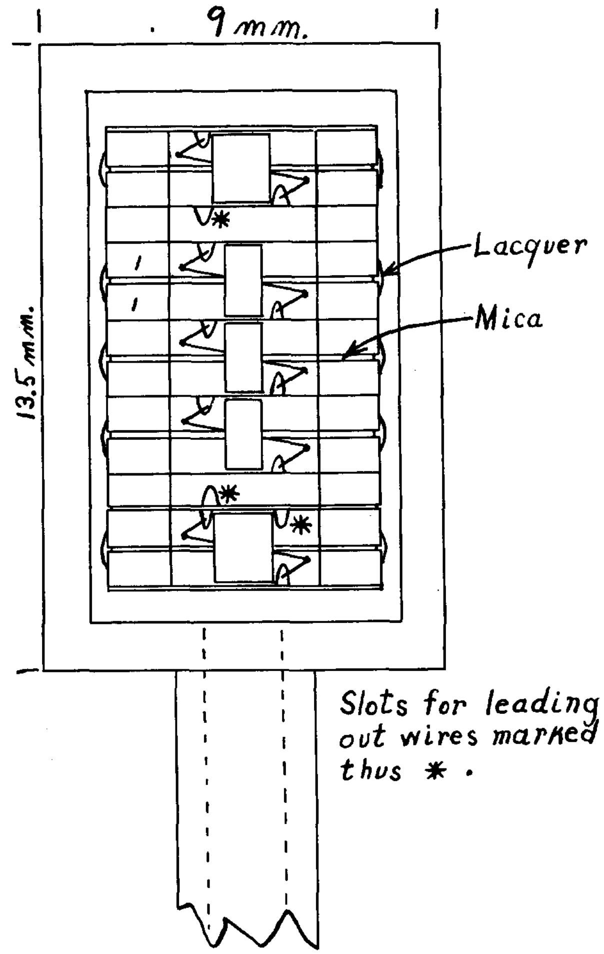

FIG. 4.

radiation would affect the two sets of elements equally and produce no deflection. A spectral line, however, is limited in length by the length of the entrance slit and will therefore pass through the regular exit slit only and will not fall on the compensating elements. The compensation is not so good for changes in temperature of the slit jaws, as the image of the jaws falls on the edge of the receivers; the jaws should, therefore, be good heat conductors so that the temperature of the regular and compensating slit jaws is the same. This style of compensated thermopile is almost as sensitive as a Type 1 because no heat is conducted from the hot to the cold junctions. By the proper use of mica separators and a copper screw (lacquered for insulation) for binding the elements together, the necessary series connections of the elements are neatly made. The inside of the case is painted with lacquer for insulation and the enameled connection wires are brought down the stem and out through a picein seal. The front of the case is covered by a window which is stuck on with quick drying lacquer. A compensated type as described is now being constructed but has not been tested as yet.

A similar compensated thermopile can be adapted to the Pfund method of resonance radiometry in which the radiation entering the spectrometer is interrupted periodically and the thermopile is connected to a freely swinging galvanometer of small damping having the same period as the interruption. The thermopile may be built with four elements, two elements receiving the radiation from the upper half of a regular exit slit and two from the lower half. These two sets of elements are connected in series opposition, one set being shunted with a copper resistance coil so adjusted that any general radiation from the parts of the spectrometer will produce no deflection. By means of a shutter, the radiation is permitted to enter only the upper half of entrance slit for say two seconds, and then the radiation is admitted to only the lower half of the slit for two seconds. This change of radiation between the two halves of the slit takes place periodically and will therefore produce an alternating deflection of an undamped galvanometer having a four second period. Such a system should be almost entirely free from drifts, both on account of the compensated thermopile used and the fact that the Pfund method itself minimizes the effect of drifts.

SENSITIVITY

An uncompensated thermopile of 15 ohms resistance built as described above was placed at one focus of the elliptical mirror shown in

Fig. 5, a slit 2.0×0.1 cm being at the other focus. The thermopile was covered by a potassium bromide window and was evacuated. When a plumbers candle was placed 1 meter in front of the slit, the thermopile generated 38 microvolts on open circuit. With the aid of the Moll relay one can have a galvanometer system which gives a deflection of 1000 mm per microvolt with this thermopile, consequently, a candle at one meter would in effect give a deflection of 38,000 mm. With this system, the Brownian movement of the coil of the primary galvanometer would give a zero unsteadiness of about 0.5 mm. When using a circuit of this nature, it is necessary that the entire circuit be enclosed in a copper shield, as any alternating currents induced in the circuit are rectified by the thermopile and produce deflections.

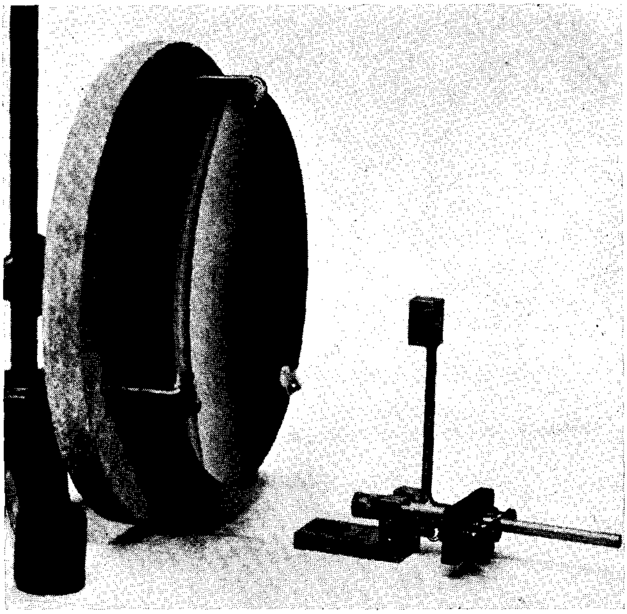

FIG. 5. *Compensated vacuum thermopile and elliptical mirror which forms a small image of the exit slit of the spectrometer on the receivers. Mirror 4.7 inches diameter, foci 3.5 and 17.5 inches from the mirror.*

TECHNIQUE OF CONSTRUCTION

As an example, the method of constructing the element of Fig. 2 will be described. One thermoelectric wire (Baker & Co.) is bismuth 0.03 mm diameter, 1 mm long and the other, Huthchins alloy, 95% bismuth, 5% tin, 0.05 mm diameter, and 1 mm long. This gives about

6 ohms resistance. The receiver is silver 1.7×0.6×0.002 mm. The wires and receivers are so light that they will stick to a needle and thus may be very conveniently handled. For most of the operations, a low power binocular microscope is necessary. A method of handling and soldering the wires due to C. F. Meyer greatly reduces the skill required. Each wire, several millimeters long, projects over the edge of a separate piece of glass to which it is held by a small weight. The two pieces of glass are moved till the wires come into position for soldering, the ends overlapping about 0.05 mm. By means of a needle, a drop of soldering flux, zinz in HCl, and a very small scraping of low melting point bismuth solder are placed on the junction. The junction is then heated by radiation from a loop of resistance wire which is at a dull red temperature, this heater being brought up to such a distance that the wires fuse together, leaving a joint which is scarcely larger than the wire itself. A comparatively large sheet of the silver foil is placed on a glass plate and blackened with Aquadag, after which the receivers are cut to size with a razor blade and a straight edge. The central point on the back of a receiver is tinned with a very small scraping of the solder. The receiver is then placed on the junction of the two wires, to which the soldering flux will hold it. The heater is again applied till the receiver is firmly welded to the junction. The flux is washed off with distilled water and a camel's-hair brush, the wires cut to length, and the element placed in position on the copper wires whose ends are already tinned. The final soldering is accomplished by touching the copper wires with the heater; the flux is then washed off these junctions. After some practice, an element can be built in this way in 30 minutes

My best thanks are due to Dr. H. B. Vincent who carefully checked the mathematical developments.