

# Determination of the Thermal Conductivity of Marble.

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If a solid sphere at a given temperature be immersed into a water-bath at another temperature, and the water be stirred vigorously, we may assume that, after a short time, the surface of the sphere is at the same temperature as the bath, provided that the substance constituting the sphere be a very poor conductor of heat, such as stone, wood, &c. In fact, most determinations of the conductivities of these substances are based on this assumption. The method used in the experiments to be described in the present paper also assumes this fact. A stone sphere of a convenient size is immersed into a bath of a constant temperature for a certain time, and is then suddenly taken out, and dipped into another bath at another constant temperature for the same length of time; then again into the first bath, and so forth. After a certain number of cycles, the temperature of any point in the interior of the sphere will be subject to a steady oscillation about a definite mean. The determination of the thermal conductivity of the substance may be effected by observing the temperature-variation at any such point, say, for simplicity the centre.

Through the kindness of Mr. Nakano of the Physical Laboratory of the Kōkwa Daigaku (Engineering College), the stone-spheres used by Professors Ayrton and Perry in their determination of the heat-conductivity of stone were placed at my disposal. After working

with them, however, I had to reject them, and get a new stone-sphere constructed.

The porphyritic stone-spheres of Professors Ayrton and Perry were found to increase in weight, if left long enough in water, especially when water was hot. At first, it seemed natural to attribute this to soaking in through the surface\*; and yet it was hard to believe that soaking, and soaking only could explain such a great amount of increase as 12 per cent. of weight, inasmuch as 12 per cent. in weight was equivalent to some 30 per cent. in volume. Besides, the hole in the sphere, which contained a thermoelectric junction, was always found to be full of water—a fact, hardly explicable by surface soaking. Various devices were tried to prevent this supposed soaking, but without any success. But when the balls were repolished, very fine cracks were discovered. These cracks, of course, fully explain the increase of weight, and the presence of water in the hole. But cracked balls, it was obvious, could not be used, and the construction of a new ball was necessary. It is to be hoped, that the cracks did not exist at the time when Professors Ayrton and Perry experimented upon these balls.

A sphere of 10.46 c.m. in radius was cut out of a block of saccharoidal marble (crystalline limestone,  $\text{CaCO}_3$ ) of density 2.71. A small hole 6 m.m. in diameter was bored into the sphere radially towards the centre. Into this a nickel-iron junction enclosed in a fine glass tube 4.2 m.m. in diameter was inserted. The junction itself protruded out of the end of the glass tube so as to be in contact with a drop of mercury at the centre of the sphere. The end of the glass tube was completely closed by a cement of Japanese varnish (*urushi*), which at the same time fixed the glass and junction-wires.

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\*Professors Ayrton and Perry seem to hint at this possibility in their paper (see Phil. Mag. 5th Series Vol. V. p. 257, last sentence of Section VII.)

The wires used for the junction were .5 m. m. in diameter ; coarser wires having been found to produce thermal effects by direct conduction from parts outside the sphere. Even the glass-tube itself was found to be a similar source of disturbance, so that it was necessary to protect the upper part of the tube from direct contact with the water. This was effected by means of a slightly larger metal tube. This metal tube was provided with three metallic strips of a quadrantal form, which, fitting close over the upper half of the sphere, were screwed to three similar strips from below. Where the tube met the three quadrantal strips, it expanded into a disc, which fitted well on the sphere near the junction-hole. After the insertion of the glass-tube containing the junction, the space between it and the wall of the hole was filled with a paste of zinc sulphate, minium, and linseed oil. A thin coating of the same paste was spread over the under surface of the disc, which when the strips were screwed tight, prevented any water from passing into the hole from the outside. By these arrangements, the heat conducted directly through wires or their connections from the part outside the sphere, was diminished to such a degree as to be inappreciable. These precautions were found to be absolutely essential.\*

Another thing to be looked to carefully was the stirring of the water in the baths. The more vigorous the stirring of the water in the hot and cold baths, the greater the range between the maximum and minimum temperatures. The reason was that when the agitation was not sufficient, the surface of the sphere was not at the same temperature as the bath itself. With increased agitation, however,

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\*Although Professors Ayrton and Perry speak of very fine wire, the wires I found in their balls could hardly be so designated; the copper was 1.3 m.m. in diameter; the iron .7 m.m. Further the copper wire, simply coated with gutta-percha and cotton, seemed to have been directly exposed to the bath, and the iron does not seem to have had any covering at all. As Professors Ayrton and Perry speak of careful insulation of wires from water and from one another, probably the wires I found were inserted by some body else afterward.

the surface temperature more nearly approached the temperature of the bath. There seemed to be a limit to this effect of stirring as indeed there ought to be, so that after a certain degree of agitation further increase caused no appreciable change in maximum and minimum temperatures. At this limit, it may be supposed that the surface temperature was same as that of the bath. The experiments were performed always with this limiting vigor of agitation.

The heating bath was made of copper of about 30 cubic decimeters in capacity, and was heated by means of a charcoal fire. The water contained in the bath was maintained always boiling. In order to accomplish this, two tubes from separate boilers were dipped into the bath so as to have their muzzles near the sphere, when the latter was in position. The steam from these tubes kept the water in a constant state of violent agitation, and this combined with the bubbling of the water itself from the bottom of the bath produced stirring enough to warrant us in assuming that the temperature of the surface of the sphere to be equal to that of the bath.

The cold bath was of about the same capacity as the hot bath, and contained water mixed with a large quantity of pounded ice. Over the bath, a tripod of wooden poles was placed, from which the sphere with its accessories was suspended. A man sitting near kept the whole apparatus constantly shaking to and fro, so that the water in contact with the sphere was constantly changing.

The stone sphere rested on a horizontal ring, which was suspended by four stout wires from the thick wooden board, which served as a cover for the bath. The board had a sliding door, which was closed, when the sphere was in the hot bath, and opened when in the cold bath. This was found necessary, as it was difficult to maintain the water in a boiling state without a cover; and then, on the other hand, when the sphere and its belongings were removed to the cold bath, the

heated board and ring seemed to retard the cooling of the ball.

At first, it was attempted to determine the temperature of the centre by the method of compensation ; that is to say, the electromotive force in the thermometric circuit was balanced by an equal and opposite electromotive force produced by a second junction inserted into the circuit. The bath into which this circuit was put was heated or cooled until the galvanometer gave no current. The temperature of this second junction would then be the same as temperature at the centre of the sphere. It was found, however, very difficult to manipulate cooling or heating of this external bath so as to keep pace with the changing temperature at the centre of the ball. The results obtained were quite irregular. The second method tried was to balance the electromotive force of the circuit (the junction not in the ball being always kept at  $0^{\circ}$  C.) by a portion of the electromotive force of a Daniel's cell. A long wire was stretched to and fro on a board a considerable number of times, and, with an additional resistance of 40 ohms, was put in circuit with the cell. The electromotive force of the thermo-junction could then be balanced by the difference of potentials between the two extremities of a portion of the wire. The wire was gauged immediately afterwards, so that the temperatures at the centre could be at once deduced from the measured lengths of the portions of wire. One of the specimens given below was carried out by this method.

The third method used was that of deflection ; that is to say, the external junction was maintained at a constant temperature ; a sensitive galvanometer was put in the circuit ; the position of the spot of light in the galvanometer-scale was read from time to time, the change of the zero point being also observed. Directly after an experiment, the galvanometer was gauged, so that the temperature corresponding to any particular galvanometer reading

could be easily found. This would be an exceedingly valuable method, if one could work far from any disturbing sources. In the present case, every precaution was taken to remove any movable piece of iron and other strongly magnetic substance from the neighborhood of the galvanometer. Also to diminish torsional set, the galvanometer-mirror was suspended by a real spider line; nevertheless, the zero-point moved as much as 3 divisions in 30 minutes. Below is given the result obtained by this method.

Owing to the necessity of using small wires for junctions, the resistance of the circuit was considerable, amounting to more than 6 ohms, so that the galvanometer was not so sensitive as might have been desired. The difference of a degree in the two junctions gave a little over 10 divisions of deflection. The thermometer used was graduated to fifths of a degree centigrade. The total range of the temperature in the second experiment was something below 45° C. and the total range of the galvanometer reading was a little below 480; we can only be sure of one division in reading; so the accuracy of the result can only extend to something like one or two tenths of a degree.

When the temperatures of points equally distant from the centre of a sphere are equal, the differential equation to be satisfied is

$$\frac{\partial u}{\partial t} = \frac{K}{c\rho} \left( \frac{\partial^2 u}{\partial x^2} + \frac{2}{x} \frac{\partial u}{\partial x} \right)$$

$u$  = temperature

$c$  = specific heat

$\rho$  = density

$K$  = conductivity

$t$  = time

$x$  = variable radius

The well-known solution of this equation applicable to the present case is \*

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\* See Thomson's Art. on Heat, in Ency. Brit., or Thomson's Math. and Phy. Papers, Vol. II, page 41. In the former  $\nu$  is put equal to  $n k$ , a misprint, which is corrected in the latter.



and  $D_i$  is to be determined by

$$B_i = 0.$$

Hence the general solution is

$$u = \frac{1}{x} \sum_{i=1}^{i=\infty} \frac{2aX}{i\pi \sqrt{\varepsilon^{-2\nu_i^{\frac{1}{2}}X} + \varepsilon^{2\nu_i^{\frac{1}{2}}X} - 2\cos 2\nu_i^{\frac{1}{2}}X}} \left\{ \varepsilon^{-\nu_i^{\frac{1}{2}}x} \sin\left(\frac{2i\pi}{T}t - \nu_i^{\frac{1}{2}}x + D_i\right) - \varepsilon^{\nu_i^{\frac{1}{2}}x} \sin\left(\frac{2i\pi}{T}t + \nu_i^{\frac{1}{2}}x + D_i\right) \right\}$$

This solution, however, is only true, when the cyclical process of heating and cooling has been repeated for an infinite number of times, so as to efface completely the trace of the initial distribution of temperature. If by repetition of the cyclical process, the initial effect be completely destroyed, then the temperature distribution would depend on the surface condition only. But the solution satisfies the surface condition, and the differential equation; therefore the value of  $u$  corresponding to any value of  $t$  and  $x$  must give the temperature at  $x$  and at  $t$ . Hence the solution is unique.

When  $x$  is made equal to zero, the value of  $u$  will represent the temperature at the centre. Denoting by  $u_0$ , the value of  $u$  for  $x=0$ , we obtain

$$u_0 = -\frac{4a}{\pi} \sum_{i=1}^{i=\infty} \frac{\nu_i^{\frac{1}{2}}X}{i\sqrt{\varepsilon^{-2\nu_i^{\frac{1}{2}}X} + \varepsilon^{2\nu_i^{\frac{1}{2}}X} - 2\cos 2\nu_i^{\frac{1}{2}}X}} \left\{ \sin\left(\frac{2\pi i}{T}t + D_i\right) + \cos\left(\frac{2\pi i}{T}t + D_i\right) \right\}$$

or changing  $D_i$  to  $\beta_i - \frac{\pi}{4}$ ,

$$u_0 = -\sqrt{32} \frac{a}{\pi} \sum_{i=1}^{i=\infty} \frac{\nu_i^{\frac{1}{2}}X}{i\sqrt{\varepsilon^{-2\nu_i^{\frac{1}{2}}X} + \varepsilon^{2\nu_i^{\frac{1}{2}}X} - 2\cos 2\nu_i^{\frac{1}{2}}X}} \sin\left(\frac{2i\pi}{T}t + \beta_i\right)$$

which might be written

$$u_0 = \alpha_1 \sin\left(\frac{2\pi}{T}t + \beta_1\right) + \alpha_3 \sin\left(3\frac{2\pi}{T}t + \beta_3\right) + \&c.$$



Now if we determine the values of  $u_0$  for different values of time, the  $\alpha$ 's and  $\beta$ 's might be determined. As the series is a rapidly converging one, we may stop at 4th or 5th term, and then with a large number of determination of  $u_0$  for different times, we may determine the values of the  $\alpha$ 's, and  $\beta$ 's by the method of least squares. There is however another, and far simpler method, which in this particular case, at least is no less accurate. The above equation might be put

$$u_0 = \alpha_1 \cos \beta_1 \sin \frac{2\pi}{T} t + \alpha_1 \sin \beta_1 \cos \frac{2\pi}{T} t$$

$$+ \alpha_3 \cos \beta_3 \sin 3 \frac{2\pi}{T} t + \alpha_3 \sin \beta_3 \cos 3 \frac{2\pi}{T} t$$

$$+ \&c. \ \&c.$$

If we multiply this by

$$\sin \frac{2i\pi}{T} t \ dt \text{ or } \cos \frac{2i\pi}{T} t \ dt,$$

and integrate from  $t=0$ , to  $t=T$ , all the terms of the right-hand member of the equation will in the usual way vanish, excepting one, which is the term of the  $i$ th order. The equation is then reduced to

$$\int_0^T u_0 \sin \frac{2i\pi}{T} t \ dt = \frac{T}{2} \alpha_i \cos \beta_i \quad \text{or}$$

$$\int_0^T u_0 \cos \frac{2i\pi}{T} t \ dt = \frac{T}{2} \alpha_i \sin \beta_i$$

The first members of these equations are simply the areas included between the  $t$ -axis and the curve.

$$y = u_0 \frac{\sin \left( \frac{2i\pi}{T} t \right)}{\cos \left( \frac{2i\pi}{T} t \right)}$$

between the limits  $t=0$ , and  $t=T$ . Now from the values of  $u_0$  and corresponding  $t$ , different values of  $y$  corresponding to  $t$  are to be found, and the curve carefully drawn on section-paper. By means of a planimeter, the quadrature can be easily effected. If

$$\frac{T}{2} \alpha_i \cos \beta_i = A_i; \quad \frac{T}{2} \alpha_i \sin \beta_i = A'_i$$

then

$$\alpha_i = \frac{2}{T} \sqrt{A_i^2 + A_i'^2}$$

$$\tan \beta_i = \frac{A_i'}{A_i}$$

By this method,  $\alpha$ 's and  $\beta$ 's can be found with an accuracy equal to that of the experiment.

The determination of the amplitude  $\alpha_i$  of any term of the series would enable us to calculate the value of the conductivity. If we were to determine all the  $\alpha$ 's, the value of  $K$  calculated from each would be same, provided that the experiment had been performed, so as to satisfy all the theoretical conditions. But, from necessary imperfections of experiment, the values would almost certainly all differ from one another. Inasmuch, however, as the first term is by far the most important, we may safely assume that the value of  $K$  calculated from it cannot be far from the truth.

In the same way, different  $\beta$ 's will give different values of  $K$ ; but for the reason just given the one obtained from  $\beta_1$  will probably be a better value than that deducible from any of the other  $\beta$ 's. In the following calculation, the values were obtained from  $\alpha_1$  and  $\beta_1$  only.

The value of  $\beta_i$  enables us to calculate  $D_i$ , and  $D_i$  is related to the other quantities by

$$\mathcal{B}_i = 0$$

Hence

$$\tan \mathcal{B}_i = 0 = \frac{\varepsilon^{-\nu_i^{\frac{1}{2}} X} \sin(D_i - \nu_i^{\frac{1}{2}} X) - \varepsilon^{\nu_i^{\frac{1}{2}} X} \sin(D_i + \nu_i^{\frac{1}{2}} X)}{\varepsilon^{-\nu_i^{\frac{1}{2}} X} \cos(D_i - \nu_i^{\frac{1}{2}} X) - \varepsilon^{\nu_i^{\frac{1}{2}} X} \cos(D_i + \nu_i^{\frac{1}{2}} X)}$$

or 
$$\varepsilon^{-\nu_i^{\frac{1}{2}} X} \sin(D_i - \nu_i^{\frac{1}{2}} X) = \varepsilon^{\nu_i^{\frac{1}{2}} X} \sin(D_i + \nu_i^{\frac{1}{2}} X)$$

putting 
$$\nu_i^{\frac{1}{2}} X = S_i$$

we find 
$$\sin(D_i - S_i) = \varepsilon^{2S_i} \sin(D_i + S_i)$$

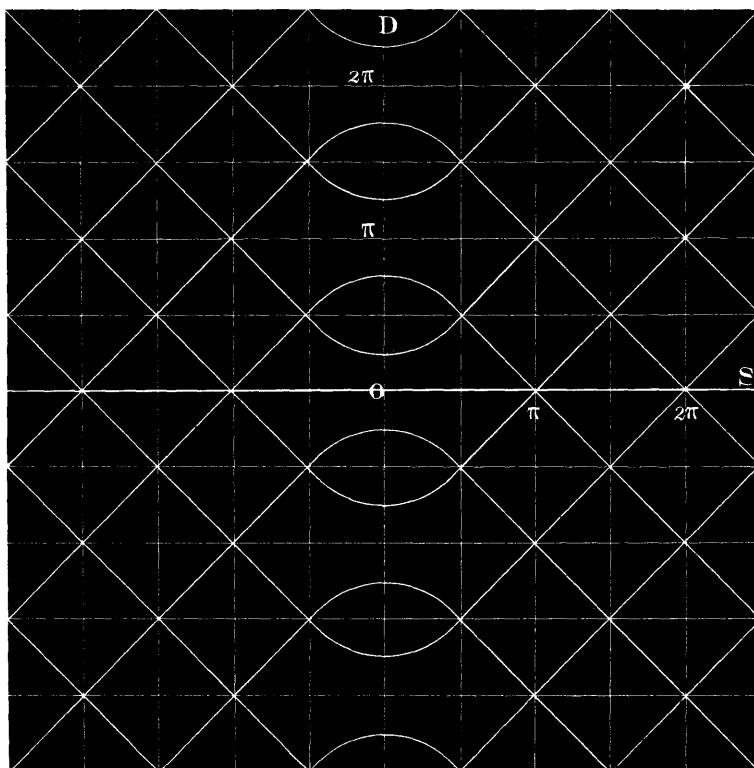
or 
$$\tan D_i = \pm \frac{\varepsilon^{2S_i} + 1}{\varepsilon^{2S_i} - 1} \tan S_i$$

And when  $S_i$  is large,

$$\tan D_i = \pm \tan(n\pi \pm S_i)$$

The following diagram shows the relation between  $S$  and  $D$ .

Curve showing relation between  $D$  and  $S$ .



From the diagram, it is easy to see that for a value of  $D$ , there are infinite number of values of  $S$ . But we are enabled to select the proper value by comparison with that obtained from the value of  $\alpha$ .

Out of many experiments, the following two are taken as specimens. In the first, the period was 50 minutes or 3,000 seconds, and the readings were taken during the 8th period from the beginning of the cyclical operation. It was found, that after the 6th period, the mean value of the temperature at a point remained sensibly constant, or in other words the trace of the initial distribution of temperature was completely effaced, so far at least as experiment can tell us. The experiment was conducted according to the potentiometer method.

Experiment on May 7—1888. The temperatures were determined by the method of potentiometer.

First Specimen Experiment. Period 3000 secs. 8th Cycle  
Zero of temperatures = 50° c.

Potentiometer Reading.	Corresponding Temperature.	Time in Seconds.	Potentiometer Reading.	Corresponding Temperature.	Time in Seconds.
94.4	-22.95	7	268.8	24.65	1762
84.2	-25.65	75	273.3	25.75	1826
76.0	-27.90	146	275.2	26.31	1875
64.0	-31.30	314	275.3	26.33	1928
66.1	-30.75	365	266.0	23.90	2037
75.4	-28.10	478	253.9	20.65	2157
99.4	-21.65	640	220.8	11.85	2322
112.1	-18.15	714	208.0	8.40	2376
117.3	-16.65	747	206.0	7.85	2394
132.8	-12.25	833	182.0	+ 1.20	2497
148.7	- 7.75	911	163.5	- 3.75	2590
161.9	- 4.25	982	153.6	- 6.40	2637
178.0	+ 0.12	1071	146.1	- 8.50	2676
187.4	2.70	1140	136.1	-11.22	2731
193.7	4.40	1180	123.1	-15.05	2802
204.2	7.40	1242	117.6	-16.60	2845
219.4	11.50	1345	106.3	-19.75	2914
231.3	14.72	1426	103.0	-20.60	2942
236.8	16.17	1528	96.8	-22.25	2982

The second column was calculated by means of the following table obtained by gauging the wire.

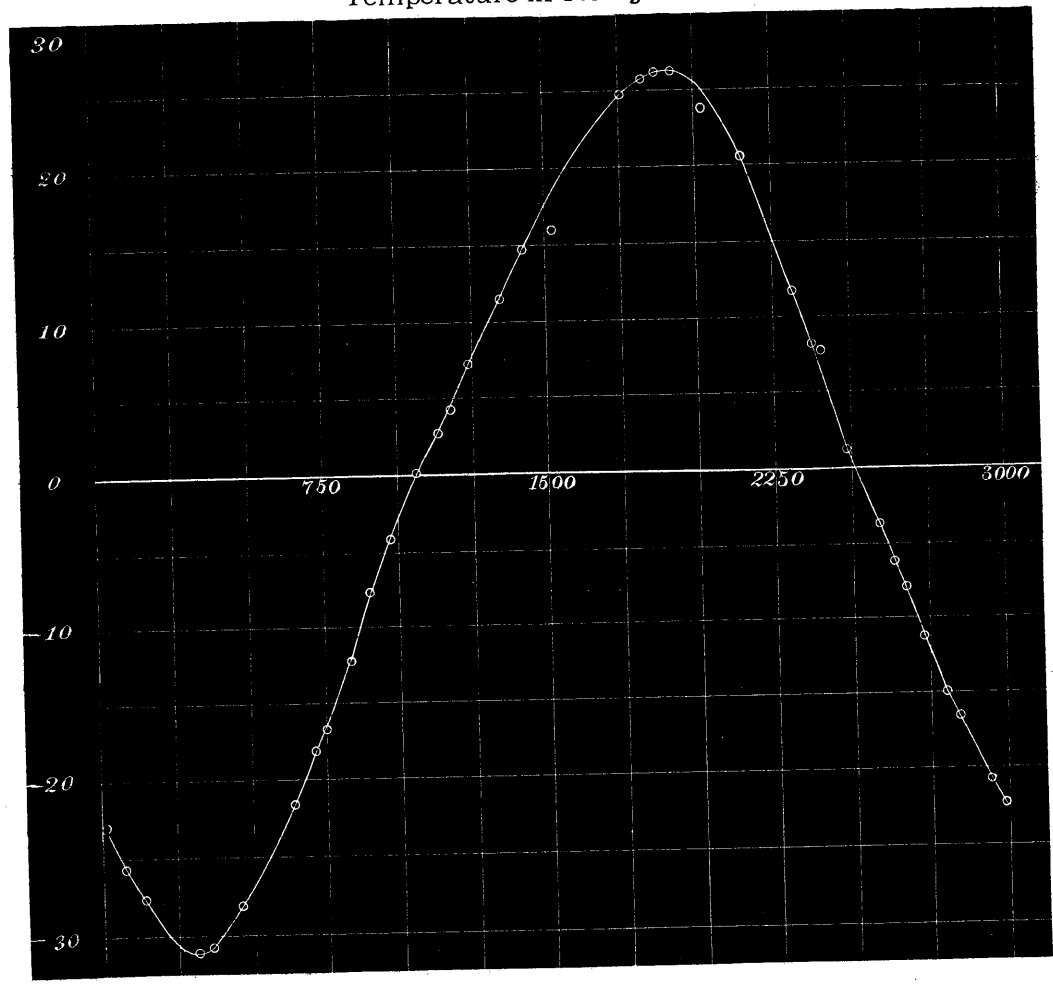
Potentiometer Reading and Temperature.

Potentiometer Reading.	Corresponding Temperature.	Potentiometer Reading.	Corresponding Temperature.
299.5	32.70	139.6	- 10.50
250.3	19.92	111.4	- 18.30
216.4	10.80	75.7	- 28.00
184.0	+ 1.85	39.7	- 38.35

A curve was carefully drawn from the numbers in the second table, and the temperatures corresponding to the numbers in the second column of the first table were carefully interpolated.

The curve representing the temperature-variations at the centre is here given.

Temperature Variation at Centre.  
Period = 3000 Sec.; 8th Cycle.  
Temperature in Centigrade.



From this curve, temperatures corresponding to every 41.6 seconds or to  $t = T \frac{5^\circ}{2\pi}$  were calculated, and the curves

$$\begin{aligned} y &= u_0 \sin 2\pi \frac{t}{T} \\ &= u_0 \cos 2\pi \frac{t}{T} \end{aligned}$$

were drawn ; careful measurements gave

$$A_1 = -24787.$$

$$A'_1 = -32294.6.$$

whence

$$\beta_1 = 52^\circ - 29' - 34''$$

$$\alpha_1 = -27.136$$

Referring to the curve showing the relation between  $D$  and  $S$ , we at once see that the value of  $S_1$  must be nearly  $\pi$ . Now assuming that  $S_1$  is near  $\pi$ ,  $\varepsilon^{-2S_1}$  would be exceedingly small, so that it is negligible in comparison with  $\varepsilon^{+2S_1}$ ; and with an assumed approximate value for  $2 \cos 2S_1$ , the value of  $\alpha_1$  gives

$$S_1 = 2.990$$

If  $S_1$  be near  $\pi$ ,  $\frac{\varepsilon^{2S_1} + 1}{\varepsilon^{2S_1} - 1}$  may be taken equal to unity for a first approximation ; then

$$\tan D_1 = \pm \tan (n\pi \pm S_1)$$

Hence

$$S_1 = 3.272 \text{ or } = 3.011$$

If we calculate  $\alpha_1$  from these values, we obtain respectively

$$\alpha_1 = -22.38 \text{ and } \alpha_1 = -26.14$$

Therefore the second value must be the first approximation to the true value.

As  $\frac{\varepsilon^{2S_1} + 1}{\varepsilon^{2S_1} - 1}$  varies very slowly when  $S_1$  is large, to calculate it,

we take  $S_1 = 3$ , and we obtain

$$S_1 = 3.012$$

Again making  $S_1 = 3.012$  in  $\frac{\epsilon^{2S_1} + 1}{\epsilon^{2S_1} - 1}$ , we get the same value

$$S_1 = 3.012$$

so that this which is the calculated value of  $S_1$  from  $\beta_1$  must be correct to a unit in the last figure. But

$$K = \frac{\pi c \rho}{T S_1^2} X^2$$

and the mean value of two specific heats for marble obtained by Regnault is .21287.\* Assuming this value and the mean value of  $S_1$  as determined from  $\alpha_1$  and  $\beta_1 = 3.001$ , we obtain

$$K = .00734 \text{ c.g.s. centigrade.}$$

Experiment on May 14—1888. The temperatures were determined by the method of deflection.

Second Specimen Experiment Zero point —347.

Period = 40 minutes 14th Cycle

Zero of Temperature = 50° c.

Galvanometer Reading.	Corresponding Temperature.	Time in Minutes.	Galvanometer Reading.	Corresponding Temperature.	Time in Minutes.
— 56	— 14.44	.5	— 144	— 24.97	6.75
— 68	— 15.90	1.0	— 143	— 24.80	7.0
— 80	— 17.30	1.5	— 140	— 24.47	7.5
— 90	— 18.50	2.0	— 135	— 23.85	8.0
— 101	— 19.80	2.5	— 129	— 23.20	8.5
— 111	— 20.94	3.0	— 121	— 22.17	9.0
— 119	— 21.90	3.5	— 113	— 21.24	9.5
— 128	— 23.07	4.0	— 61	— 15.07	12.0
— 135	— 23.85	4.5	— 58	— 14.70	12.5
— 140	— 24.47	5.0	— 47	— 13.35	13.0
— 142	— 24.77	5.25	— 33	— 11.70	13.5
— 144	— 24.97	5.5	— 21	— 10.34	14.0
— 145	— 25.07	5.75	— 10	— 9.07	14.5
— 145	— 25.07	6.0	+ 3	— 7.54	15.0
— 145.5	— 25.10	6.25	16	— 6.07	15.5
— 145	— 25.07	6.5	29	— 4.54	16.0

\* See Clark's Constants of Nature, Specific Heat Table.

Galvanometer Reading.	Corresponding Temperature.	Time in Minutes.	Galvanometer Reading.	Corresponding Temperature.	Time in Minutes.
32	- 4.17	16.5	242.5	19.26	27.5
89	+ 2.33	18.5	241	19.10	27.75
100	3.56	19.0	240.5	19.03	28.0
111	4.83	19.5	239	18.86	28.25
123	6.23	20.0	237	18.60	28.5
134	7.46	20.5	235	18.43	28.75
146	8.86	21.0	233	18.23	29.0
156	9.93	21.5	225	17.40	29.5
168	11.23	22.0	217	16.60	30.0
177	12.53	22.5	208	15.56	30.5
188	13.40	23.0	197	14.43	31.0
199	14.63	23.5	185	13.13	31.5
207	15.50	24.0	174	11.86	32.0
216	16.50	24.5	159	10.23	32.5
221	16.90	24.75	146	8.86	33.0
225	17.40	25.0	74	+ .56	35.5
228	17.73	25.25	60	- 1.00	36.0
231	18.10	25.5	47	- 2.40	36.5
234	18.33	25.75	33	- 4.10	37.0
237	18.60	26.0	19	- 5.70	37.5
239	18.86	26.25	+ 6	- 7.20	38.0
240.5	19.03	26.5	- 8	- 8.77	38.5
242	19.23	27.0	- 19	- 10.10	39.0
242.5	19.26	27.25	- 32	- 11.60	39.5

## Galvanometer Reading and Corresponding Temperature.

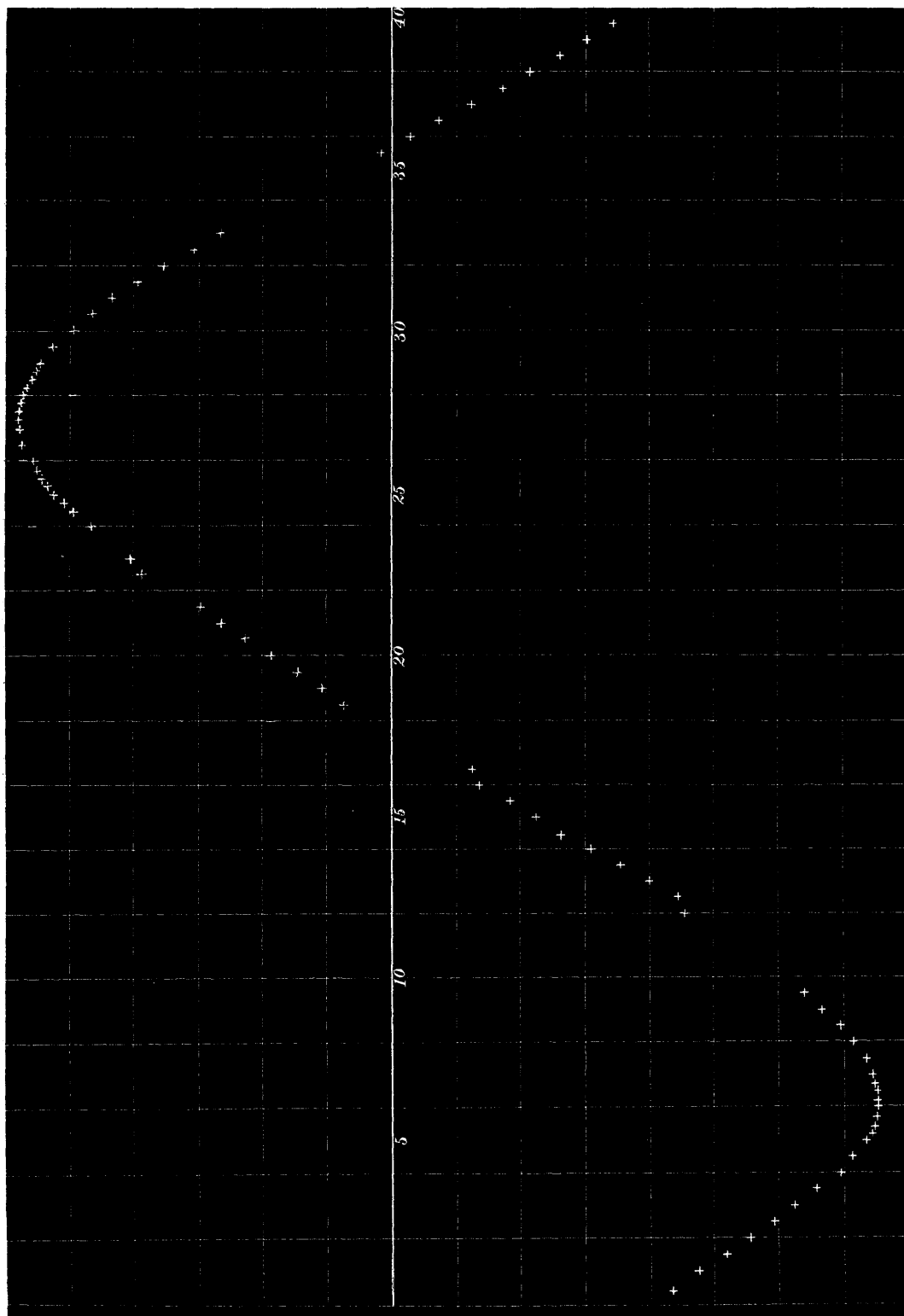
Zero point of the galvanometer = -347.

Galvanometer Reading.	Corresponding Temperature.	Galvanometer Reading.	Corresponding Temperature.
279	23.10	- 1	- 7.98
217	16.60	- 43	- 12.90
195	14.20	- 98	- 19.40
142	8.40	-140	- 24.50
95	+ 3.05	-157	- 26.60
+ 50	- 2.05	-206	- 32.20

The second column of the first table was obtained by interpolation from the curve drawn from the second table. The curve showing the temperature variation at the centre is



Period = 40 minutes, 1400 cycle.  
Temperature in Centigrade.



The curve is even more free from irregularities than the curve for the first experiment. The same process of calculation was performed in order to obtain the values of  $A_1$  and  $A'_1$ ; and they are

$$A_1 = -21942.9; A'_1 = -12547.6$$

And consequently

$$\alpha_1 = -21.064; \beta_1 = 29^\circ - 45' - 44''$$

Calculating from  $\alpha_1$  we get for  $S_1$  the value

$$3.358$$

Calculating from  $\beta_1$  is in the same way as before, we get

$$S_1 = 3.407$$

If we take the mean value of the two, we obtain

$$S_1 = 3.383$$

Then

$$K = \frac{\pi \epsilon \rho}{T S_1^2} X^2 = .00722.$$

The results from the two experiments do not differ from one another by more than  $1\frac{1}{2}$  per cent, and the mean value of  $K$  from the two experiments is

$$K = .00728$$

The value, however, differs much from values obtained by previous experimenters, as may be seen from the appended table.

G. Forbes.....	White marble.....	.00115
Péclet.....	Marble.....	.0048
Depretz .....	Fine-grained marble, (density=2.68)	.0097
Ditto.....	Sugar-white, coarse-grained marble (density = 2.77) .....	.0077*
Herschel .....	Marbles, limestone, etc.....	.0047 to .0056

The second marble experimented upon by Depretz seems to have been very much like the marble used in my experiments, and the value

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\* See Everett's Physical Constants.

is very much like the one obtained by me. We may therefore assume that the value  $K = .0073$  is not very far removed from the true value of the thermal conductivity of white coarse-grained marble.

The present mode of experimenting seems to be open to criticism in one respect only—namely, the method of determining the temperature at the centre. With a distinct improvement in this particular, the accuracy of the final result would be greatly enhanced. It is hoped that such improved experiments may be undertaken at some future time.

The experiments here described were all performed by Messrs. K. Ikeda and M. Ogawa, chemical students, while working in the Physical Laboratory, under my direction.

