THE HALL EFFECT AND ALLIED PHENOMENA IN TELLURIUM.

By Peter I. Wold.

THE following investigation of the galvano- and thermo-magnetic properties of tellurium was prompted originally by a desire to find if any trace of the Hall effect could be detected in a liquid metal.

In view of the fact that the Hall effect has been found in gases[1] and that the theories on this subject give no reason to believe that it should not be found in liquids, experiments have been made at various times attempting to prove or disprove its existence. See for example the work of Everdingen,[2] Roiti,[3] Chiavassa,[4] and Bagard.[5] Tellurium was selected for the study because of its exceedingly large Hall effect at ordinary temperatures.

In the preliminary tests made on tellurium with the above object in view the specimen used showed such unusual and interesting properties that a more thorough investigation of the various galvano- and thermo-magnetic constants seemed justified. This was particularly true in view of the fact that the apparatus necessary for the investigation at the melting point lent itself well to investigation at other temperatures.

Apparatus.

A Weiss electro-magnet, with pole pieces 10 centimeters in diameter, was used. With these pole pieces a very uniform magnetic field, about 7 centimeters in diameter, could be obtained. This gave a maximum field strength of 10 to 15 thousand gausses per cm.^{2} for the distances between the pole faces which were ordinarily used.

The various effects were all measured by the potentiometer method and the most sensitive galvanometer used had a sensitivity of 130 mm. per microvolt at a scale distance of 4 meters.

Preliminary experiments with the magnet showed that there was considerable residual magnetism on breaking the magnetizing current

[1] Wilson, Phys. Rev., 3, 375, 1914.
[2] Leiden Comm., No. 41, 1898.
[3] Journ. de Phys., 1883.
[4] Ellettricista, 6, 1897.
[5] Journ. de Phys., Ser. 3, T. 5, p. 499, 1896.

and that the amount of residual magnetism depends on the current strength and distance between the poles. It was apparent that for accurate work one could not rely upon a previously plotted curve giving the magnetic field for different values of current. The importance of this will appear later in considering certain parts of the work. Accordingly, arrangements were made to measure the change in the magnetic field, both on making and on breaking the magnetic circuit and at the time of taking observations on the Hall or other effect.

The specimen of tellurium to be studied was fused in a hydrogen atmosphere to prevent oxidation. Generally it was found best to place the tellurium in a test tube of combustion tubing with a small hole blown in the side, about four centimeters from the bottom. Hydrogen was then allowed to flow over the metal and escape through the hole, where it was ignited. The tube was then placed in an electric furnace and the molten metal was quickly poured into a mold, with the hydrogen flowing over it continually.

In its final form the mold consisted of a plate of asbestos slate 4 mm. thick in which a hole 4 cm. by 2 cm. was made. This was closed by cementing to the bottom a thin piece of the same material. The various electrodes, shown in Fig. 1, were embedded in grooves in the plate before the casting was made, being held in place by plaster of paris.

Heating was obtained by means of a double electric furnace. The inner furnace consisted of two brass plates 15 cm. square and spaced 5 mm. apart. Nichrome ribbon was wound around this for a heating coil, being insulated from the brass plates by mica. The second furnace was made of sheets of asbestos board properly spaced to just admit the first furnace and was also wound with nichrome ribbon, the windings being at right angles to those of the first furnace. By this arrangement the temperature gradient through the ends of the furnace was very much reduced and a very uniform temperature was obtained throughout the central portion of the furnace. The furnace, complete and mounted, was about 2 cm. thick. The currents through the two furnace windings were independently controlled.

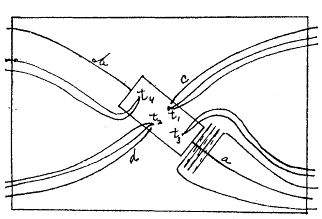

Fig. 1.

In order to obtain the various readings desired four electrodes and four thermo-junctions were connected to the specimen, as shown in Fig. 1. The primary electrodes, *a* and *b*, consisted of platinum ribbon extending across the ends of the specimen, which became fused to the specimen in casting. Copper wires, fused to these platinum strips, served as leads.

The Hall and Nernst effects were measured by means of the electrodes *c* and *d*, consisting of copper wires fused to short pieces of platinum. Copper cannot be used directly in contact with tellurium for it dissolves readily in molten tellurium.

As near to the last two electrodes as possible were placed two copper constantan junctions, t_1 and t_2. For reasons which will appear later, these two junctions were insulated from but embedded in the tellurium. The insulation consisted of a glass sheath about 1/20 mm. thick. Arranged longitudinally in the specimen were two platinum-platinum rhodium junctions, t_3 and t_4. These junctions were fused into the tellurium, being in metallic contact therewith.

The temperature gradient required in the specimen for the thermomagnetic effects was obtained by a small heating coil of 8 turns threaded through holes in the base plate near one end of the specimen, as shown in Fig. 1. By suitable control of the current in this coil any reasonable temperature gradient could be obtained.

Hall Effect.

The preliminary observations were made on a specimen of tellurium, obtained from Baker and Co., of fair degree of purity. The specimen was 2 cm. square. It was repeatedly heated to a molten condition and search made for the Hall effect. With the galvanometer then in use no definite results were obtained. Certain deflections were noted but they were irregular and may well have been due to mechanical motion of the liquid metal. Readings were taken at various temperatures during the heating and the results consistently showed a change from a positive to a negative Hall effect at a temperature in the neighborhood of 125° C. followed by a reversal to a positive value in the neighborhood of 225°. These results were so surprising that it seemed well to subject them to more careful examination. It was thought that the effect might be due to impurities and consequently work was started to secure especially pure tellurium. This part of the work was done by Mr. D. T. Wilber, of Cornell University. A new supply of tellurium was obtained from Eimer and Amend and subjected to the following treatment:

$$Te + 4HNO_3 = TeO_2 + 4NO_2.2H_2O,$$

$$3TeO_2 + 2CrO_3 + 6HNO_3 = 3TeO_3 + 2Cr(NO_3)_3 + 3H_2O.$$

This was evaporated with an excess of HNO_3 until the telluric acid, $H_2TeO_4.2H_2O$ or $TeO_3.3H_2O$, separated out. This was recrystallized six times by dissolving in hot water, then adding nitric acid and cooling. It was washed once with alcohol to remove traces of $Cr(NO_3)_3$.

The pure acid was reduced to the metal by boiling with recrystallized hydrazine hydrochloride:

$$2TeO_3 + 3N_2H_4.2HCl = 2Te + 6HCl + 3N_2 = 6H_2O.$$

The finely divided metal was washed with water to free it from hydrochloric acid, hydrazine or telluric acid.

The metal was then reduced to the massive form by melting in a section of combustion tubing, there being a continuous stream of hydrogen passing over and through the mass. This product was treated in the manner described on page 3 in order to get it in the desired form.

Measurements were made to find the relation between the Hall effect and the magnetic field at constant temperature. The results obtained, by taking a number of runs at different temperatures, are given in Table I., in which

H = strength of field in gausses per cm.[2]
E_a = Hall effect in microvolts with the magnetic field in one direction.
E_b = Hall effect with field in other direction.
E = mean of these two.
R = Hall constant.
$D = E_a - E_b$.

R is obtained from the usual expression for the relation between the various quantities involved; viz.,

$$R = \frac{E}{Hib},$$

where i is the current density and b is the distance between the Hall electrodes.

Fig. 2 shows graphically the relation between the Hall effect, repre-

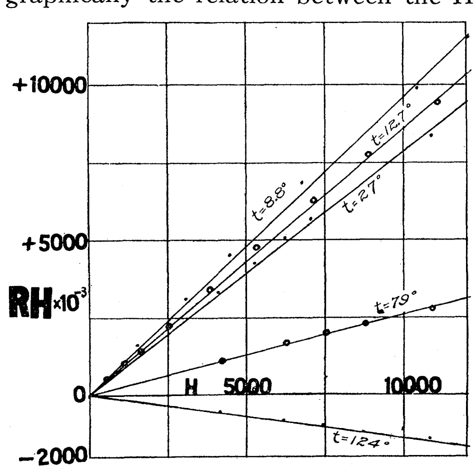

Fig. 2.
Hall Effect and Magnetic Field.

TABLE I.

Hall Effect.

t = 12.7° C. Current = .234 amp.

H	E_a	E_b	E	$RH \times 10^{-3}$	R	D	$D/H^2 \times 10^{+7}$
586	+259	+263	+261	+516	+881	− 4	
1,151	524	506	515	1,015	881	+18	
1,684	726	724	725	1,413	839	2	7
2,595	1,154	1,139	1,147	2,222	857	15	22
3,884	1,747	1,722	1,735	3,375	868	25	17
5,365	2,460	2,415	2,438	4,740	884	45	16
7,193	3,301	3,204	3,253	6,250	869	97	19
8,930	4,043	3,870	3,957	7,710	864	173	22
11,134	4,936	4,692	4,814	9,390	844	244	20
t = 27.1° C. Current = .236 amp.							
577	+229	+228.5	+229	+446	+773	+ 0.5	15
1,660	674	655	665	1,289	776	19	69
3,060	1,235	1,220	1,228	2,360	771	15	16
4,160	1,724	1,697	1,711	3,300	793	27	16
5,320	2,217	2,166	2,192	4,240	798	51	18
6,280	2,648	2,564	2,606	5,050	804	84	21
7,080	2,975	2,864	2,920	5,650	798	111	22
8,820	3,636	3,474	3,555	6,890	781	162	21
10,950	4,432	4,174	4,303	8,350	763	258	22
t = 79.0° C. Current = .234 amp.							
2,160	+290	+276	+283	+535	+248	+14	30
4,265	580	539	560	1,080	254	41	23
6,310	865	789	827	1,650	262	76	19
7,580	1,069	952	1,011	1,970	260	117	20
8,790	1,207	1,039	1,123	2,260	257	168	22
10,900	1,511	1,299	1,405	2,755	253	212	18

sented by RH, and the magnetic field. The curves are straight lines, the slope of each being the sum of the ordinates divided by the sum of the abscissæ for the points shown for that curve. It will be noted that in each case the points for intermediate values of field lie above the line, this departure from the straight line relation can also be noted by observing the values for R in Table I. In each case, even where the effect is reversed, the intermediate values for R have a higher value, considered positively. The discrepancy appearing in the first two lines of the first set is probably due to the greater relative error in taking observations in weak fields.

A certain amount of dissymetry was observed in the Hall effect as obtained for fields of different directions. This is shown under the column headed D and will be discussed later in connection with the change of resistance.

Ettinghausen Effect.

The Ettinghausen effect, or the transverse galvanomagnetic temperature difference, was measured by means of the copper constantan thermo-junctions, t_1 and t_2 of Fig. 1. By connecting these two junctions in opposition it was possible to increase the accuracy of the work greatly. To do this, however, it was necessary that the junctions should be insulated from each other. This was done in the manner described elsewhere. The arrangement was such that a scale deflection of 1 mm. was equivalent to .0002°. As a rule measurements on the Ettinghausen effect were taken along with those on the Hall effect. Upon application of the field the reading for the Hall effect was taken quickly—a few seconds being sufficient—and then the attention was turned to the Ettinghausen effect. This effect was given at least a minute in which

Table II.

Ettinghausen Effect.

H	Δt	$P \times 10^5$
1,668	.006	+ 8.06
3,316	.009	6.05
6,330	.014	4.93
9,632	.029	6.71
11,750	.033	6.27
13,450	.035	5.81
15,190	.041	6.03
15,640	.043	6.14
	t = 8.8°.	
1,577	.0058	+ 7.12
3,110	.0116	7.20
4,520	.018	7.55
6,807	.025	7.05
10,482	.038	6.88
12,625	.046	7.03
15,390	.060	7.47
	t = 27.1°.	
577	.0035	+11.8
1,660	.011	12.7
3,060	.020	12.7
4,160	.024	11.2
5,320	.029	10.6
6,280	.035	10.9
7,080	.039	10.7
8,820	.042	9.3
10,950	.059	10.5

to build up. Considerable difficulty was found in deciding when the deflection had reached its maximum. This was due to a drift caused by slow temperature changes in the specimen, which might be in one direction or the other. In finding the Ettinghausen effect under any conditions temperature readings were taken in the order and with the magnetic quality of 0, +, 0, −, 0. This gave four temperature changes. With the primary current reversed a similar set of four temperature changes was obtained. The mean of these eight readings is given in the table as a value for Δt under the given conditions.

The values obtained in a number of different runs, showing the relation between this effect and the magnetic field, is given in Table II.

In this table Δt is the transverse temperature difference set up or caused by the magnetic field. P is the Ettinghausen constant as defined in the usual manner by the equation

$$P = \frac{\Delta t}{Hib},$$

in which i is the current density and b the distance between the junctions. The results are shown graphically in Fig. 3, in which Δt is used for or-

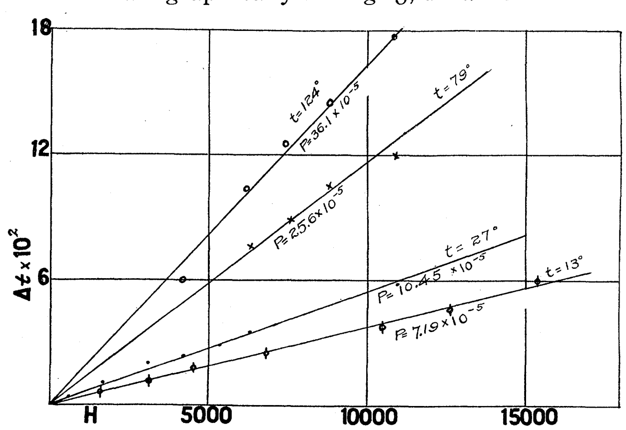

Fig. 3.

Ettinghausen Effect and Magnetic Field.

dinates and field strength for abscissæ. Considering the relatively large errors which enter into the measurement of such small temperature changes under such conditions the results seem to justify the conclusion that the Ettinghausen effect in tellurium is proportional to the magnetic field.

The value for P found for tellurium by Ettinghausen is $+ 20 \times 10^{-5}$. Lloyd[1] gives $P = 14 \times 10^{-5}$ to 29×10^{-5} at 65° and for $H = 5500$.

[1] Amer. Journal of Science, 12, p. 57, 1907.

Longitudinal Effect.

A third electromagnetic effect is that commonly known as the longitudinal effect, and which is commonly expressed as change in resistance. By means of the platinum wires of the junctions t_3 and t_4 the potential between two points in the specimen, arranged longitudinally, could be found. In series with the specimen was a standard resistance. Connections were made from this to a potentiometer connected to a very sensitive galvanometer and currents could then be measured accurately to one part in 20,000. Two potentiometers were adjusted simultaneously and, in spite of variations in the battery current, instantaneous values of the current and of the potential difference between the two points in the specimen were obtained. Upon application of the magnetic field there was a change in the potential difference in the specimen indicating a change in resistance. The results obtained in two runs are given in Table III., in which H is the field strength, W_0 is the resistance

Table III.

Resistance.

H	W_0	$w'/W_0 \times 10^5$	$w''/W_0 \times 10^5$	$w/W_0 \times 10^5$	$w/W_0H^2 \times 10^{13}$	$D \times 10^5$	$D/RH \times 10^{12}$
1,588	.56335	+ 74.6	− 40.0	+ 17.3	+687	115	751
3,085	313	+ 194.8	− 26.6	+ 84.1	+890	221	748
4,430	666	+ 317	− 2.6	+ 157.2	+801	320	750
6,730	429	+ 636	+ 129.4	+ 383	+847	507	782
10,352	231	+1208	+ 439	+ 824	+768	769	770
12,515	222	+1548	+ 646	+1097	+700	902	749
15,300	222	+2092	+1028	+1560	+666	1064	722
1,690	.58918	+ 56.8	− 28.0	+ 14.4	+505	85	642
3,120	916	+ 155	− 27.0	+ 64.0	+657	182	744
4,340	913	+ 239	− 4.9	+ 117	+624	244	717
5,660	892	+ 372	+ 48.3	+ 210	+655	324	732
6,340	895	+ 455	+ 90.7	+ 273	+679	364	732
7,130	735	+ 560	+ 162	+ 361	+710	398	713
8,840	752	+ 755	+ 251	+ 503	+645	504	728
10,960	758	+1049	+ 438	+ 744	+620	611	725

in zero magnetic field during the observations at the value of field indicated, w' is the change in resistance with the magnetic field in one direction, w'' is the change with the field in the opposite direction, and w is the mean of these. D is the difference between w' and w''. The positive value of w/W_0 indicates an increase of resistance.

The change in the value of W_0 during the course of a run is due to slight temperature drift. It will be shown later that the resistance of tellurium is very senstitive to temperature changes.

In view of the fact that this longitudinal effect does not change direction with the change in direction of the magnetic field it has been assumed that the effect should be proportional to the square of the magnetic field. This law is fairly well obeyed in some substances. In case of bismuth, which has been studied the most carefully in this respect, it appears that the law holds for weak fields, but for stronger fields the effect is nearly proportional to the first power of the magnetic field. Column six in the table shows how this law holds in this case. The variations between the different values of w/W_0H^2 seem to be entirely irregular and are probably due to experimental errors.

Referring to Table I. it is to be noticed that there is a dissymmetry in the value of the Hall effect, depending on the direction of the magnetic field. In his work on bismuth Van Everdingen[1] has shown that this dissymmetry can be explained by means of the change in resistance. If the Hall terminals are not on an equipotential line, but are slightly displaced, a component of the total potential drop through the specimen, due to the primary current, will show itself at the Hall terminals and, of course, will not reverse with the magnetic field. Upon the application of the magnetic field the Hall effect will be superimposed upon this potential difference, in the one case adding to it and in the other case subtracting from it. The Hall effect is obtained by taking the difference between the potentiometer reading for zero field and for field H. If the component of the potential at the Hall terminals remains constant there will be no error from this source. If, however, the current remains constant and the resistance changes on the application of the field it is obvious that the component potential across the Hall terminals will change in the same proportion. Consequently the value of the Hall effect obtained by taking the difference between the potentiometer readings with and without the field will be in error. If the change in resistance reversed with the magnetic field it would be impossible to separate it from the Hall effect and so find the true value of the Hall effect. Since it does not reverse it is apparent that in the one case it will increase the value of the Hall effect and in the other case decrease it so that a correct value for the Hall effect is obtained by taking the mean of the two values so obtained. This method has been followed out as shown in Table I., in which E_a gives the Hall effect obtained with the field in one direction and E_b that obtained with the field in the opposite direction. The correct value of the Hall effect is the mean of these two, given under E.

If this dissymmetry is due to the change in resistance it should follow

[1] Leiden Communication, No. 26, 1896.

the same law. Assuming, from the results in Table III., that the change in resistance is proportional to H^2 then there should be a linear relation between D and H^2, or D/H^2 should be a constant. Column 8 of Table I. shows the values obtained for D/H^2. Excluding the values for very weak fields, in which the dissymmetry is very small and subject to relatively large errors, it will be noticed that the agreement among the values of D/H^2 is very satisfactory, thus giving a verification of Van Everdingen's theory.

A dissymmetry in the change of resistance was also found, the value being always larger with the magnetic field in one direction than in the other. It even occurred that in weak fields there was an apparent decrease in resistance with the field in one direction. Columns 3 and 4 of Table III. show this. The mean of the two values was, however, positive in all cases. It occurred to the author that a similar line of reasoning may be used to explain this dissymmetry as was used in the case of the Hall effect. If the two leads, by means of which the potential drop along the specimen is measured, are not exactly on a line of current flow it will occur that, upon the application of the magnetic field, a component of the Hall effect will be found across these potential leads. Since the resistance change does not reverse with the magnetic field and since the Hall effect does reverse, in the one case the resistance will be increased by the component of the Hall effect and in the other case will be decreased. Consequently the correct value of the resistance change will be obtained by taking the mean of the two values so obtained. Since the Hall effect is very large in tellurium it is not surprising that the small component of it which comes across the potential leads should more than overbalance the resistance increase, giving an apparent decrease in resistance. Since the resistance increases as the square of the magnetic field while the Hall effect increases with the first power only the increase in resistance finally outstrips the Hall effect. If this dissymmetry is due to the Hall effect it should be proportional to it and consequently there should be a linear relation between D and RH, or D/RH should be a constant. In column 8 of Table III. will be found the values of D/RH. The agreement is very satisfactory indeed.

One other galvanomagnetic effect, *i. e.*, the longitudinal change in temperature, was sought for but, if present, was masked by a component of the Hall effect. If the junctions t_3 and t_4 had been insulated from the specimen, as were t_1 and t_2, it might have been possible to find it.

Thermomagnetic Effects.

In order to study the thermomagnetic effects a small heating coil near one end of the specimen was arranged as described on page 3. Since there was no corresponding cooling agent at the other end the average temperature of the specimen was raised and thus the study at the lower temperatures was limited. The temperature gradient was measured by means of junctions t_3 and t_4, which are spaced 2.6 cm. apart and approximately equidistant from the center.

NERNST EFFECT.

The relation between the Nernst effect and the magnetic field is shown in Table IV. The average temperature is given by t and the temperature gradient by dt/dl. The second column gives the Nernst effect in absolute

TABLE IV.

Nernst Effect.

H	$QH \times 10^{-2}$	Q
$t = 45.8°$ C., $dt/dl = 21.4/2.6 = 8.23$.		
2,230	6.3	.283
4,340	12.5	.287
6,520	18.8	.288
7,890	22.3	.283
9,080	25.3	.279
11,250	29.7	.264
$t = 204°$ C., $dt/dl = 17.8/2.6 = 6.85$.		
2,180	5.8	.264
4,330	11.6	.268
6,500	17.7	.273
7,870	20.9	.266
9,120	23.7	.260
11,210	28.4	.253
$t = 43.1°$ C., $dt/dl = 19.6/2.6 = 7.54$.		
2,160	11.1	.512
4,270	22.1	.517
6,400	33.5	.523
7,830	40.8	.522
9,030	46.4	.514
11,200	55.2	.492

units for a plate of unit dimensions in which there is unit temperature gradient. The third column gives the constant for the Nernst effect, where Q has the usual significance expressed by the relation

$$Q = \frac{E}{H \frac{dt}{dl} b}.$$

Lloyd[1] gives $Q = .36$ at 33°.

[1] Amer. Journ. of Sci., 12, p. 57, 1907.

The relation between QH and H is also shown graphically in Fig. 4. The slopes of the straight lines shown are equal to the sum of all the ordinates of the points shown divided by the sum of all the abscissæ. It will be noted that there is a slight departure from the straight line relationship, there being a slight curvature upwards. This same is

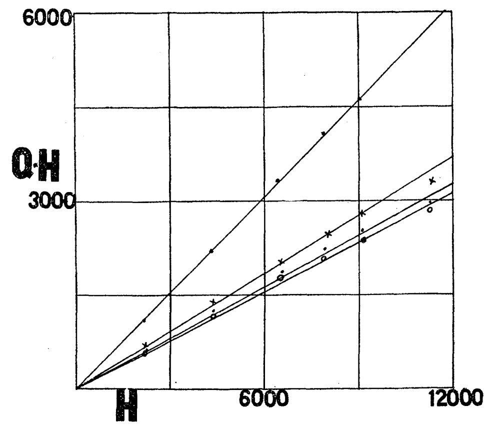

Fig. 4.
Nernst Effect and Magnetic Field.

apparent from a perusal of the values of Q in Table IV., the values of Q increasing slightly with increase of field and then decreasing. The same effect was noted in the case of the Hall effect.

Leduc Effect.

The relation between the Leduc effect and the magnetic field is shown in Table V. The manner of taking observations was the same as that given for the Ettinghausen effect, the same order of magnetic changes being followed and being repeated. Each value of Δt is therefore the mean of eight readings.

Table V.

Leduc Effect.

$t = 114°.,\ dt/dl = 30°/2.6 = 11.5°,\ Q = 1.07.$

H	Δt	$SH \times 10^{+3}$	$S \times 10^{+6}$
3,120	.412	20.4	6.5
6,390	.729	36.1	5.7
7,750	.973	48.1	6.2
8,920	1.162	57.5	6.5
10,700	1.243	61.6	5.8

The Leduc constant is obtained from the usual equation

$$S = \frac{\Delta t}{H \dfrac{dt}{dl} b}.$$

The values for S show a good agreement considering the great difficulties in the measurement of such small temperature differences. The conclusion is justified that the Leduc effect is proportional to the magnetic field.

Lloyd[1] found $S = +4 \times 10^{-6}$ for tellurium at 34°.

An unusually large value for the Nernst effect was obtained at this time, being given by $Q = 1.07$.

Relationship Between the Various Effects and Temperature.

The dependence of these various effects upon temperature has been studied up to the melting point of tellurium and will be discussed in the same order as for the dependence upon the magnetic field.

Hall Effect and Temperature.

In their original investigations on tellurium Ettinghausen and Nernst[2] stated that the Hall effect decreases with an increase of temperature. Smith[3] has also recently investigated the effect of temperature up to 370° C. Smith finds a rapid drop as the temperature rises until 180° C. is reached. Between 180° and 275° the effect decreases slowly. At 275° Smith notes a sudden rise of about 100 per cent. after which there is again a gradual drop. Smith connects this discontinuity with the fact that there are probably two crystalline forms present in tellurium, this fact being pointed out by Haken[4] as a result of work done on the resistance and the thermo-electric power of tellurium.

In the preliminary work, mentioned previously, the author was surprised to find that the Hall effect started with a positive value and diminished rapidly with rise of temperature, changing into a negative value and later, with further rise in temperature, reversing to a positive value again. The same results were obtained repeatedly. The fact that a reversal in the Hall effect in tellurium had never been noted led to the suspicion that it was due, in this case, to some impurity in the specimen used. At the same time further investigation of this unusual phenomenon seemed justified. Accordingly tellurium, purified in the manner previously indicated, was subjected to careful study. The results of the preliminary trial were fully verified, as shown in Fig. 5, in which the ordinates represent Hall effect for a constant magnetic field of 7,580 C.G.S. units, and a constant current of .2425 ampere. The initial value of the Hall effect differs radically in different successive runs but in every case there is a

[1] Amer. Journ. of Sci., 12, p. 57, 1907.
[2] Acad. Wiss., Wien, Anz., p. 173, 1886.
[3] Phys. Rev., 5, p. 351, 1913.
[4] Ann. d. Phys., 32, p. 291, 1910.

definite double reversal in the sign of the Hall effect. The initial value depends, apparently, upon the heat treatment. The runs were taken in the order in which the curves are numbered. The runs 1, 2 and 3 followed each other on successive days and it appeared as though the extent to which the specimen became negative was decreasing and that

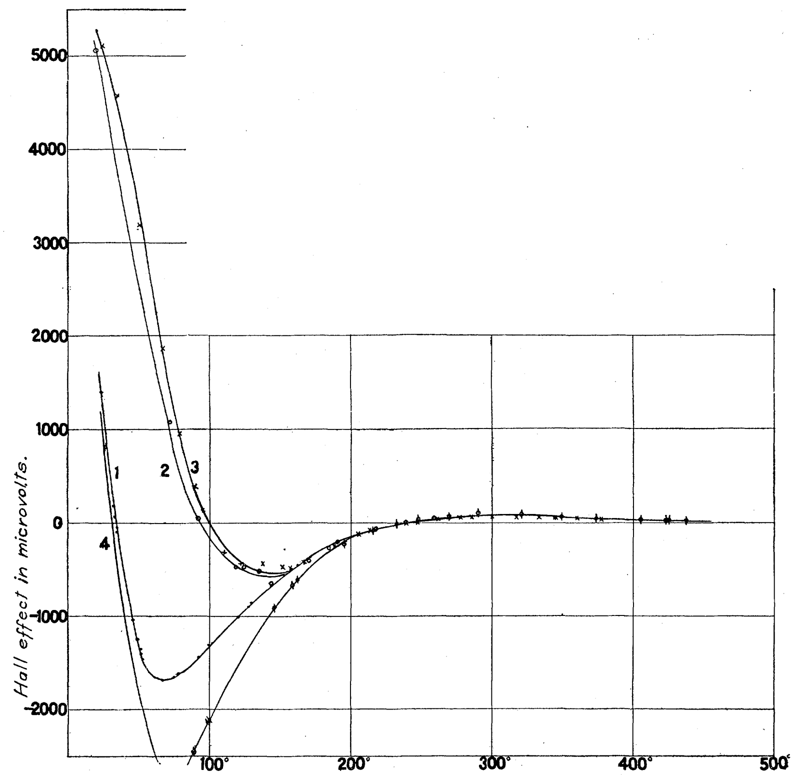

Fig. 5.

Relation between Hall Effect and Temperature.

finally the change would not appear. After this, various other properties were studied and the specimen was subjected to a varied heat treatment. Another run was then made on the Hall effect resulting in Curve 4 which shows an enormous negative value. Not expecting such results large temperature steps were taken and consequently the turning point of the curve was entirely missed. One can therefore only estimate the magnitude of the negative Hall effect attained in this run. It is of importance to note that, while there is a great difference in the curves at lower temperatures, the curves gradually approach each other and cross to a positive value at the same temperature, viz., 245° C. From there on the curves agree within the errors of observation.[1]

According to Haken and others tellurium occurs in two crystalline modifications. The α modification is stable below 354° C. and the β modification is stable above this temperature. As tellurium is cooled from this temperature the β form goes over into the α form, but the process is rather slow and, in general, some of the β form will not have time to pass over before it is cooled to such an extent that it cannot make the transition. At ordinary temperatures, then, both forms are present and the relative amounts will depend on the previous heat treatment.

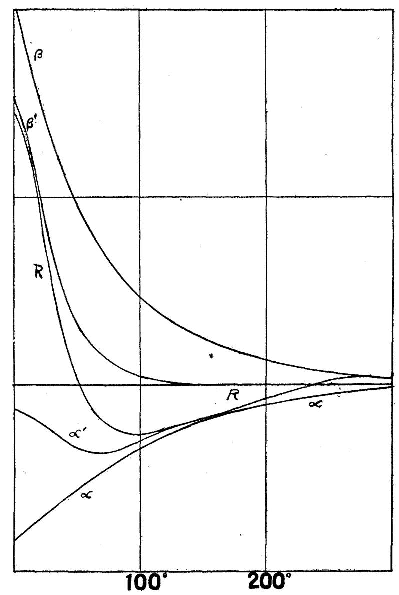

Fig. 6.

Relation between Hall Effect and Temperature.

The peculiar effects here obtained may be tentatively explained on the basis that the β modification has a positive and the α modification a negative Hall effect. Referring to Fig. 6 we may assume, for the present, that the Hall effect for pure β tellurium would be given by the curve β and that for pure α tellurium by the curve α. At room temperature there may be a large proportion of the β tellurium, but with rise in temperature the mobility of the molecules increases and they go over in the α form. Assuming the mass law to hold in this case and bearing in mind the continually decreasing amount of this form, the actual Hall effect contributed by the β tellurium would be given by curve β'. Similarly, in view of the relatively small initial but continually increasing

[1] Since writing the above a chemical analysis of the tellurium used in this work has been made by Prof. R. P. Anderson, of Cornell University. In spite of the superiority of the method used and the great care exercised in the preparation of the tellurium it seemed possible that the unusual results obtained were due to the presence of some impurities, in particular tellurium dioxide. The analysis showed that, aside from tellurium dioxide, the impurities were too small to be detected. The powdered tellurium contained about 17 per cent. of the dioxide. The average of two tests on the fused metal gave a tellurium content of 100.5 per cent. The analyst states that this high result is, without doubt, due to a slight oxidation of the tellurium during the drying operation at the close of the analysis. The error is in the direction to indicate high purity and in any event the amount of oxide present in the fused metal is exceedingly small and is certainly no larger than in that used by previous experimenters.

amount of α tellurium, the actual Hall effect due to it would be given by curve α'. The sum of these two curves, *i. e.*, curve R, would give the resultant Hall effect, which shows a reversal to the negative sign at a temperature depending on the heat treatment.

At a higher temperature the β tellurium becomes stable and consequently the α reverts into the β form, with its positive Hall effect. As a result we find the curve R crossing the axis to a positive value. Having reached a maximum when all the α has been transformed in β tellurium, it follows the regular law of decrease for the β tellurium.

In Fig. 6 no attempt has been made to give the curves quantitative values. The figure is qualitative only.

The above hypothesis can probably be tried out by giving the specimen a systematic and varied heat treatment, and it is hoped that a thorough investigation along this line can soon be made.

It is to be noted that the actual temperatures of reversal are materially below the temperature of 354° C., given by Haken as the transition temperature.

Ettinghausen Effect and Temperature.

Simultaneously with the readings on the Hall effect, resulting in the curves just discussed, readings were taken on the Ettinghausen effect. The values obtained for the constant P are plotted in Fig. 7. Curve 1

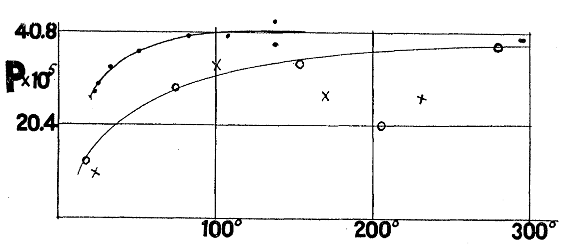

Fig. 7.

Relation between Ettinghausen Effect and Temperature.

corresponds to Curve 1 of Fig. 5. The points obtained during the runs corresponding to Curves 2 and 3 are shown, respectively, by circles and by crosses. While the values do not agree with those of Curve 1 they show in all cases a decided increase in the value of the effect as the temperature increases. Both of the last two runs show a big drop in value in the neighborhood of 200° C. and then an increase. In view of the difficulties in taking these readings there is some doubt as to whether this drop is a real effect or is due to experimental errors.

RESISTANCE AND LONGITUDINAL EFFECT WITH TEMPERATURE.

While readings were being taken on the Hall effect and the Ettinghausen effect readings were also taken on the resistance and the change of resistance in the magnetic field. The method used has been described.

Fig. 8 shows the relation between specific resistance and temperature.

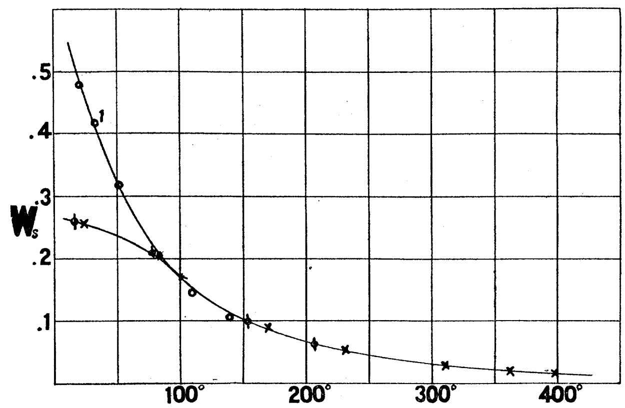

Fig. 8.

Relation between Resistance and Temperature.

The ordinates are expressed in ohms per cm.[3] Curve 1 corresponds to Curve 1 of Fig. 5. It will be seen that the resistance at room temperature depends on the heat treatment and that in the neighborhood of 150° C. the curves come together after which they repeat consistently. The results obtained from the runs 2 and 3 agree throughout. The specific resistance at room temperatures is enormous, being about 500,000 times that of copper.

Tellurium has been classed by Koenigsberger[1] with certain other materials as a conductor of the second class. Its decrease of resistance with increase of temperature has been explained as due to the fact that the number of free electrons, which are effective in producing metallic conduction, is not constant, as is assumed in ordinary metals, but increases with increase of temperature. In ordinary metallic conduction the increase of resistance with temperature is due to the increased collision activity of the electrons. This factor is also effective in conductors of the second class but is masked by the great increase in the number of free electrons. According to Koenigsberger a temperature is reached at which the further increase of electrons is much decreased or ceases entirely. From this point on these conductors should show an increase of resistance with rise in temperature. No such effect can be detected in the resistance

[1] Ann. d. Phys., 32, p. 179, 1910.

curve of tellurium up to a temperature of 400° C., and there seems to be no indication of its appearance before the liquefaction temperature of about 450° C. is reached.

The dependence of the magnetic change of resistance on the temperature is shown in Fig. 9, in which the ordinates give $\Delta w/W$, *i. e.*, the ratio of the increase of resistance in the magnetic field to the resistance in zero field. The constant field strength used was 7,580 gausses and the current was .2425 ampere. As in the case of the resistance curves, the results repeat above about 150° C. Curve 1 corresponds to Curves 1 of Figs. 5 and 8. The largest relative increase occurs when the resistance is largest.

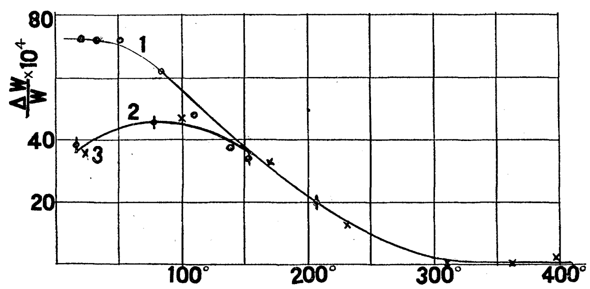

Fig. 9.

Relation between Longitudinal Effect and Temperature.

Nernst Effect and Temperature.

With increase of temperature the Nernst effect is found to increase quite rapidly to a maximum and then decrease continually to the liquefaction temperature. This is shown in Fig. 11.

Thermo-electric Power and Temperature.

Measurements were made on the thermo-electric power of tellurium, use being made of the platinum terminals of the thermo-junctions 3 and 4. In view of the very large thermo-electric power measurements could be made with small temperature difference between the two junctions, ranging from 2 to 10 degrees. The small temperature gradient still permitted measurements of the Nernst effect. In view of the comparative smallness of the Nernst effect, the Hall effect could also be obtained by first measuring the Nernst effect and then sending a primary current through the specimen. The potential difference last found would give the sum of the Nernst and Hall effect. Knowing the former the Hall effect could then be obtained. Thus it was possible to obtain, simultaneously, values of the Hall and the Nernst effects and of the thermoelectric power. The results are shown in Fig. 10 and Fig. 11. Curves

1 and 2 of Fig. 10 and Curve 3 of Fig. 11 show, respectively, the Hall effect, the thermo-electric power and the Nernst effect. Curves 1′, 2′ and 3′ are the corresponding curves for a similar run. There seems to be no particular relationship between the curve for the Nernst effect

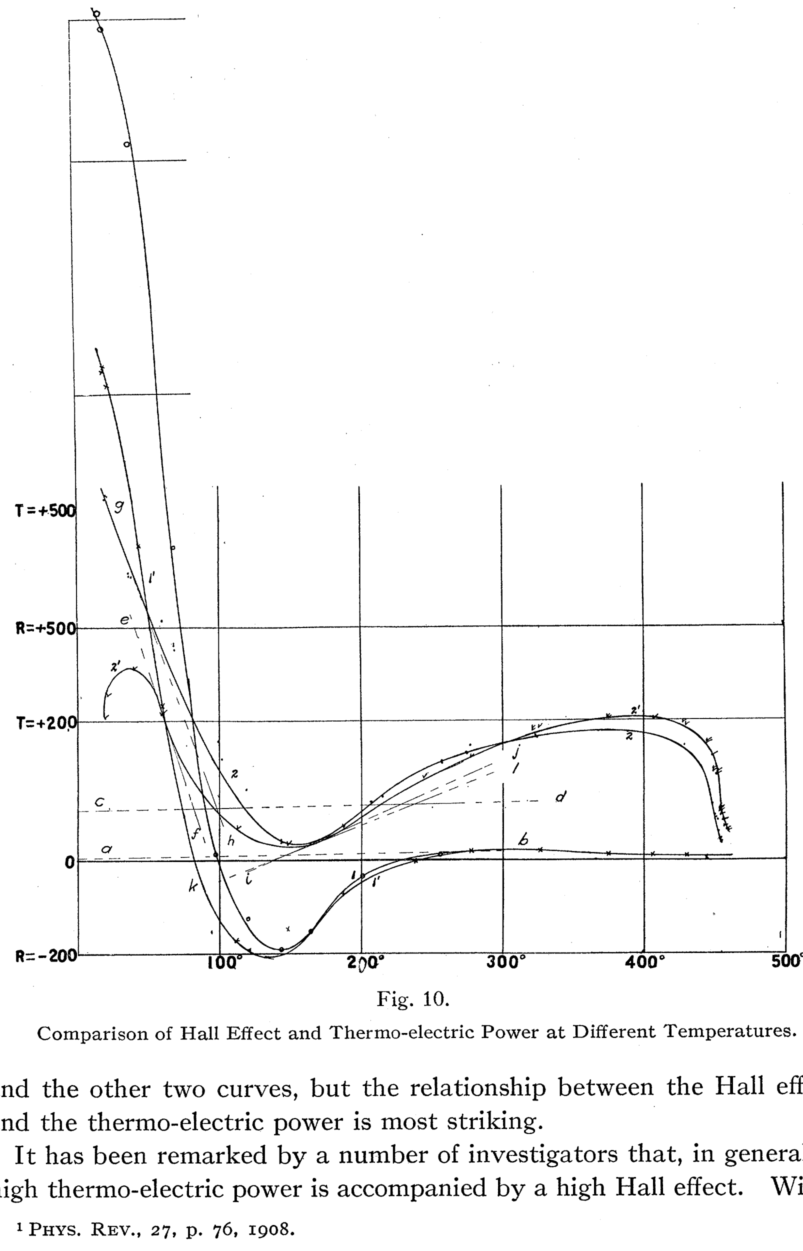

Fig. 10.

Comparison of Hall Effect and Thermo-electric Power at Different Temperatures.

and the other two curves, but the relationship between the Hall effect and the thermo-electric power is most striking.

It has been remarked by a number of investigators that, in general, a high thermo-electric power is accompanied by a high Hall effect. Wick[1]

[1] Phys. Rev., 27, p. 76, 1908.

has arranged a large number of substances according to their thermo-electric powers and finds that, with few exceptions, the Hall effect follows the same order, both in magnitude and in sign.

In this work, however, we have an unusual and remarkable curve for the Hall effect accompanied by an unusual and remarkable curve for thermo-electric power (which is ordinarily an approximately straight line) and following it so closely in form that the two curves might well be mistaken for each other. The author is not aware of any case in which such an intimate relationship between Hall effect and thermo-electric power has been shown. One is almost compelled to believe that the thermo-electric power should reverse with the Hall effect. On one or two occasions, earlier in the work, a reversal in the thermal E.M.F.

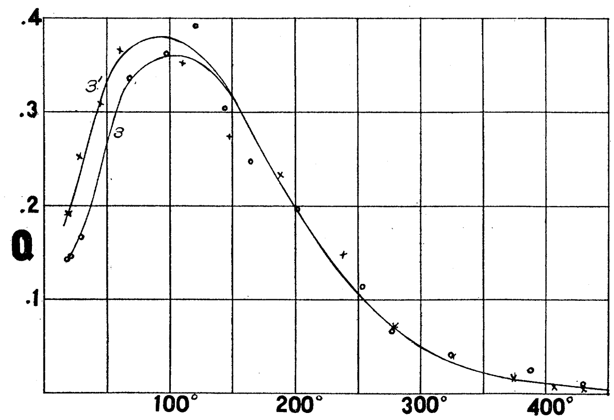

Fig. 11.

Relation between Nernst Effect and Temperature.

was found, but at that time was laid down to error in observation. During the more careful test this reversal has not occurred, but the form of the two curves together suggest that this might well be expected and is a matter depending on the heat treatment.

The thermo-electric power is here given with respect to platinum. The lead line, $a - b$, is shown slightly above it. The lead line has been taken as the standard in thermo-electric measurements because of the fact that its Thomson effect is very nearly zero. The slope of the thermo-electric power line, with respect to lead, gives the Thomson effect for any given material. So far as the Thomson effect is concerned we might equally well take any line parallel to the lead line as our standard and lead has been chosen because it is that metal which has the smallest Thomson effect, as a result of which its thermo-electric power line is practically horizontal. It is apparent then that lead is not a fundamental standard but one of convenience. A line, *c–d*, has been drawn parallel to the lead line and, for the present, will be considered as the base line for thermo-electric power. If tellurium occurs in two crystalline forms, with a relatively large proportion of β tellurium "caught" at room temperature, as previously suggested, the first part of the curves shown will apply closely to the properties of the β modification. A gradual transition commences as soon as the temperature rises. The tangent to the Curve 2 in its early stages, shown by the dotted ling *g–h*, represents the thermo-electric power for the relatively pure β modification. The point where this line intersects our new base line indicates the temperature at which the thermo-electric power reverses with respect to this base line. It will be noted that this is the same temperature—about 99° C. —as that at which the corresponding Hall effect reverses, as seen by Curve 1.

The line *e–f* similarly represents the thermoelectric power in the early stages of Curve 2′. This line intersects the new base line at the temperature 83° C., which is the same temperature as that at which the corresponding Hall effect reverses in sign, as shown by Curve 1′.

Going to the other side of the minimum points of these curves, we must conclude that the transformation into the α modification is complete when a temperature of about 185° C. has been reached. The lines *i–j* and *k–l* seem to fairly represent the slopes of the thermo-electric power curves for this temperature region, and therefore are the thermo-electric power curves for the pure α modification. The temperatures at which these lines *i–j* and *k–l* intersect the base line *c–d* are the same as those at which the corresponding Hall effects reverse from the negative to the positive signs.

It is apparent that there is a reasonable amount of freedom in choosing the location of the line *c–d* as well as the tangents *e–f* and *g–h*, at the same time there was no difficulty in bringing about the remarkable agreement between the points of intersection noted above and it is an interesting possibility that we may here have the basis for the location of a more fundamental line than the lead line from which to measure thermo-electric forces. The author has, however, no theoretical considerations to support the experimental evidence.

The change in slope of the thermo-electric power lines beyond 250° C. is to be noted. Here we are having the change from the α into the β tellurium. There is probably a large time lag in this transformation, and therefore the slope of the pure β tellurium is not reached till we are near the melting point.

Leduc and Longitudinal Thermomagnetic Effects.

It was expected that the relation between temperature and the Leduc effect would be found. Unfortunately one of the transverse thermo-junctions was broken during one of the heat runs and consequently no readings have been taken.

Attempts were also made to find the effect of the magnetic field upon the thermo-electric power as well as upon the longitudinal temperature gradient. There was clear evidence of the latter at least, but the results have been so inconsistent and irregular that they are not given.

Hall Effect in Liquid Tellurium.

Mention was made earlier of preliminary attempts to find the Hall effect in liquid tellurium. These attempts were repeated with the more elaborate apparatus but with substantially the same results. In spite of the greater precautions to eliminate disturbances it was found impossible to obtain consistent results. Transverse potential differences were obtained which were large compared to those which were obtained just previous to the melting of the metal; but these deflections were irregular in size and, at times, in direction. The author is of the opinion that the deflections noted were due chiefly, if not entirely, to mechanical motions of the liquid under the action of the magnetic field upon the primary current. Furthermore, that in the form of apparatus used, these disturbances would always be so large as to mask any Hall effect which might be present.

As far as the author is aware the Hall effect has never been found in an amorphous substance, with the exception of gases, mentioned previously. It would, therefore, be of as much interest to find it in a solid amorphous substance as in a liquid. It also seemed that, if tellurium could be obtained in an amorphous condition, the finely divided metallic precipitate, as obtained after the chemical purification, was certainly amorphous. Accordingly a specimen was prepared from some of this precipitate by pressure, sufficient to make a fairly compact mass but far from sufficient to cause the metal to flow. A Hall constant of $R = 60$ was found. A micro-photograph was then taken of some of the material with the result shown in Fig. 12. It is clear that the material used, in spite of its finely divided state, is crystalline and not amorphous.

In this connection it may be mentioned that the conviction has been growing in the mind of the author that the crystalline structure of a substance is not merely important but is necessary for the presence of the Hall effect, as we know it in general. It is true that it has been found in gases and it is possible that it exists to a slight extent in liquids; but such

Hall effects are simple and conform to simple theories, whereas in solids we are dealing with phenomena of great complexity the explanation of which must be on an entirely different basis so that it is a question whether they should even be looked upon as the same phenomena.

Heat Conductivity.

Measurements were made on the heat conductivity of the specimen last under investigation, both with and without a magnetic field. The

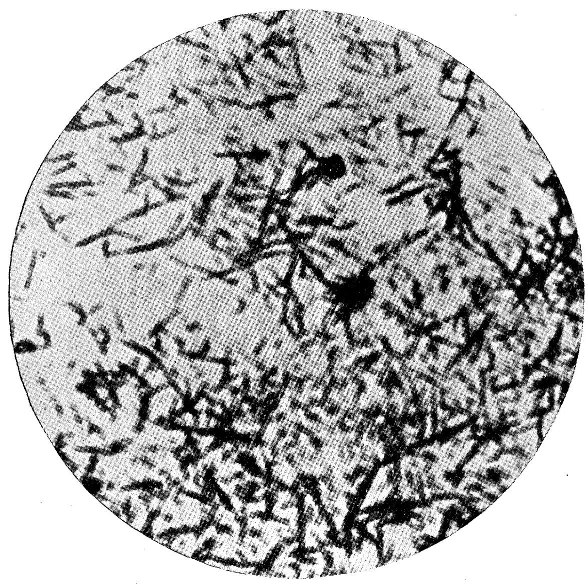

Fig. 12.

Microphotograph of Finely Divided Tellurium. (Magnification = 300 diameters.)

work was carried out with Dr. R. W. King[1] and by an ingenious method recently developed by him for finding the heat conductivity. This method consists, essentially, in measuring the velocity of propagation of a sinusoidal heat wave through the specimen. The method is particularly adapted for measurement in such a case as this. This work, which has been done only recently, must be considered as preliminary and it is hoped that the matter may be carried further at a later time. The results are as follows:

It has been assumed that the specific heat remains constant, that is, it is independent of the magnetic field. The last value for the conductivity was found after the magnetic field had been removed.

[1] King, Phys. Rev.

t = 45.3°, Density = 6.25, Spec. heat = .05.

Magnetic Field.	Coef. of Heat Conductivity.	Per Cent. Change of Conductivity.
0	.0145	
6650	.0120	19
0	.0140	

The increase of electrical resistance, or decrease in electrical conductivity, under the same magnetic field was about .4 per cent.

The only datum on this matter which has come to the attention of the writer is that given by Lloyd[1] in which he states that he found a decrease of 10 per cent. in the heat conductivity in a magnetic field of 4,700 gausses. This being a longitudinal effect we may assume that it follows the H^2 law. Using the figures above we have $19/(6{,}650)^2 = 43 \times 10^{-8}$. Using Lloyd's figures we have $10/(4{,}700)^2 = 45 \times 10^{-8}$.

SUMMARY.

The results of this experimental work lead to the following conclusions:

1. Up to 12,000 gausses the Hall and the Nernst constants show themselves to be nearly independent of the magnetic field, with indications of a slight maximum value in the neighborhood of 6,000 gausses. Within the errors of observation the Ettinghausen effect and the Leduc effect are proportional to the magnetic field.

2. The magnetic change of resistance shows itself closely proportional to the square of the magnetic field.

3. A dissymetry of the Hall effect was found to be proportional to the square of the field strength, *i. e.*, to the longitudinal effect, thus verifying Van Everdingen's explanation of the dissymetry.

4. A marked dissymetry in the longitudinal effect was found. This dissymetry is proportional to the field strength and, therefore, to the Hall effect. This dissymetry can be explained in a manner similar to Van Everdingen's explanation of the Hall dissymetry.

5. The value of the various constants, at room temperature, depends greatly upon the previous heat treatment. This is particularly true of the Hall constant for which, under certain conditions, enormous values —as high as 2,000—were obtained.

6. The Hall effect, initially positive, decreases rapidly with rise of temperature, reverses to a negative value at a temperature below 100° C., depending on the heat treatment, and reverses to a positive value again in the neighborhood of 240° C. An explanation can be given on the assumption that tellurium occurs in two crystalline forms which may be

called the α tellurium and the β tellurium. The α modification is stable below about 200° C. and the β modification is stable above this temperature. There is a large time lag in the transformation from the one form into the other which accounts for the great influence of the heat treatment.

7. The Ettinghausen effect and the Nernst effect increase quite rapidly with rise in temperature. The Nernst effect reaches a maximum at about 100° C. after which it decreases rapidly. There are indications that the Ettinghausen effect also reaches a maximum at this temperature and then decreases.

8. The resistance and the longitudinal effect decrease rapidly with rise in temperature but show no reversals and no discontinuities.

9. The Hall effect and the thermo-electric power with respect to temperature give the same form of curves, showing a very intimate relationship between the Hall effect and the thermo-electric power. By the choice of a new standard from which to make measurements the thermo-electric power has a double reversal at the same temperatures as for the Hall effect.

10. Attempts were made to detect the presence of the Hall effect in liquid tellurium but without definite results. Rather large potential differences were found but they were irregular in magnitude and direction so that it was concluded that the effects noted were due to mechanical motions of the liquid.

11. Measurements were made on the heat conductivity of tellurium, both with and without a magnetic field. A large decrease in the heat conductivity was found when in the magnetic field. This decrease was much greater than the decrease in electrical conductivity under the same conditions.

In conclusion I wish to express my thanks to the Rumford Committee, which bore part of the expense of this investigation. My thanks are also due to Professor Nichols and Professor Merritt for the continual interest and assistance which they have given to this work.

Cornell University, 1915.

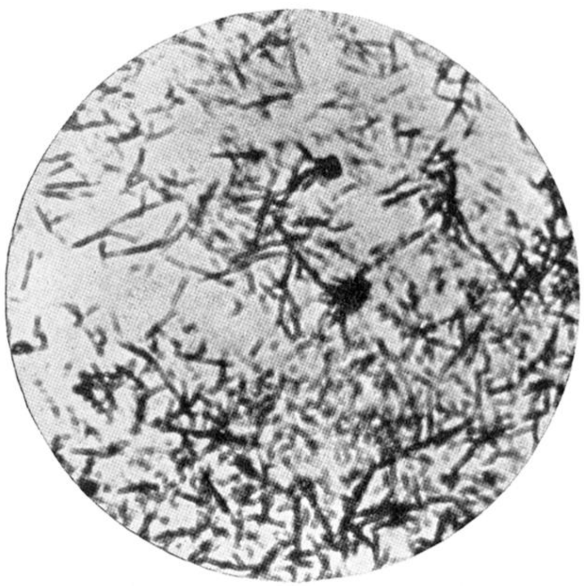

Fig. 12.
Microphotograph of Finely Divided Tellurium. (Magnification = 300 diameters.)