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THE

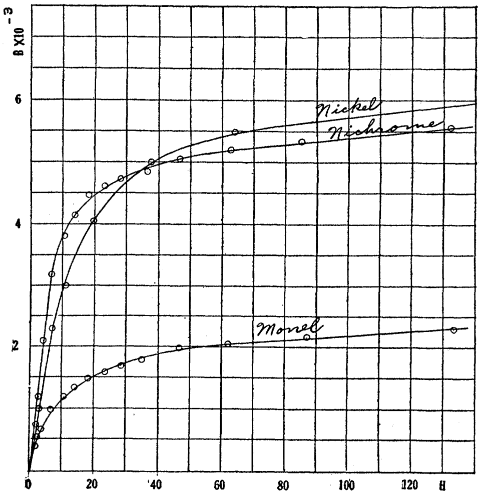
PHYSICAL REVIEW.

THE HALL EFFECT AND SOME ALLIED EFFECTS.

By Alpheus W. Smith.

The Hall Effect in Magnetic Alloys.

In an earlier paper[1] the author has examined the influence of temperature on the Hall effect in iron, nickel and cobalt. The results on these metals suggested a similar study of this effect in some magnetic alloys. For this purpose the two alloys, monel and nichrome, and three silicon steels were chosen. Monel is an alloy containing about 68 per cent. nickel, 1.5 per cent. iron, 1 per cent. manganese, and 29.5 per cent. copper. Nichrome is an alloy of nickel, iron, chromium and manganese.



Magnetisation Curves for Monel, Nichrome and Nickel.

Fig. 1.

The magnetization curves for these two alloys together with the magnetization curve for nickel are given in Fig. 1. The latter curve is taken

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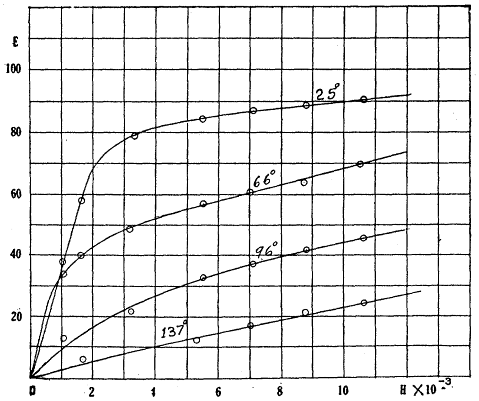
[1] Phys. Rev., 30, pp. 1–34, 1910.

from the work of Honda and Shimizu.[1] Under corresponding conditions the permeability of monel is about one half that of nickel. For fields less than 30 dynes the permeability of nichrome is greater than that of nickel but for greater fields the opposite is true. The three steels which were examined will be referred to as Steel I., Steel II. and Steel III. Steel I. and Steel II. were high silicon steels. The former contained 3.80 per cent. silicon, 0.025 per cent. carbon, 0.010 per cent. manganese, 0.06 per cent. phosphorus, 0.025 per cent. sulphur, and 0.05 per cent. aluminum. An analysis of Steel II. was not made, but it contained about the same amount of silicon as Steel I. Steel III. contained 0.25 per cent. silicon and the same amounts of the other elements which were present in Steel I. From these alloys plates of the usual form were cut for the study of the Hall effect. These plates were about 1.6 cm. wide and 3.5 cm. long. The thicknesses of the plates were as follows: Steel I., 0.0361 cm.; Steel II., 0.0332 cm.; Steel III., 0.0351 cm.; nichrome, 0.0830 cm.; and monel, 0.0625 cm.

The apparatus differed only in minor details from that used in the former paper and the method of procedure was essentially that used in the study of the Hall effect in nickel, iron and cobalt. For the details of the apparatus and the method of procedure reference is made to the paper already cited.



Hall Effect in Monel.

Fig. 2.

In Fig. 2 have been plotted the Hall electromotive forces in monel for different magnetic fields for four temperatures. Fig. 3 contains the corresponding results for nichrome at six different temperatures. Fig. 4 shows the behavior of the Hall electromotive force in the steels at room

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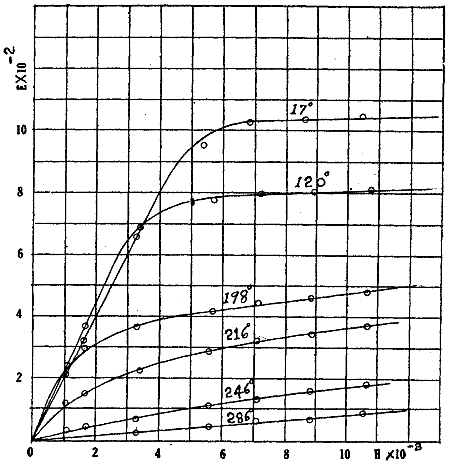
[1] Phil. Mag. (6), 10, p. 553, 1905.

temperature. For the sake of comparison the case of iron and that of nichrome have been included. In each of these figures the Hall electromotive forces which have been plotted are the electromotive forces which would be observed if a current of one absolute unit flowed in a plate one centimeter in thickness. The magnetic fields are in absolute units and the temperatures in degrees Centigrade.

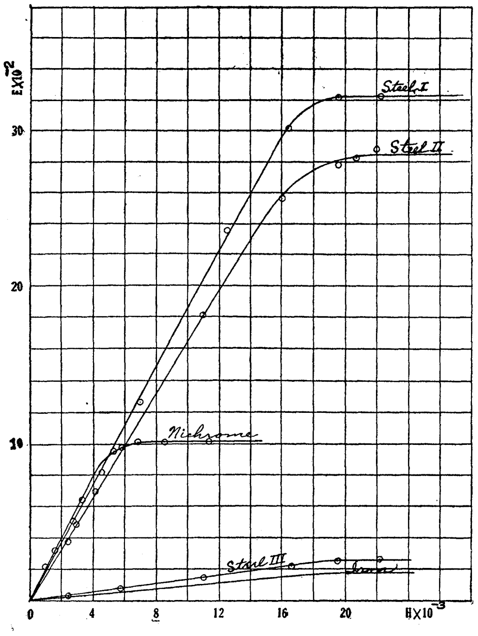
In either monel or nichrome at room temperature the Hall electromotive force is at first proportional to the intensity of the magnetic field. When saturation begins to be reached this proportionality fails. After the characteristic knee in the curve has been passed the Hall electromotive force increases slowly with further increase in the magnetic field. Saturation occurs earlier in monel than in nichrome. An increase in temperature causes a decrease in the Hall effect except that in monel for fields less than 1,000 C.G.S. units there is a small increase between 25° C. and 66° C. and in the case of nichrome there is for fields less than about 3,000 C.G.S. units a small increase between 17° C. and 120° C. When the temperature of the monel has reached 137° C. and that of the nichrome 286° C. the Hall electromotive force becomes proportional to the magnetic field as in the non-magnetic metals. At room temperature the Hall effect in monel is about three times its value in nickel and its direction is the same in the two cases. In nichrome it is about sixteen times as large as in nickel and its direction is opposite to that in nickel. Fig. 4 shows the influence of silicon on the Hall effect in iron. The curve for iron is taken from an earlier paper. Steel III., which contained 0.25



Hall Effect in Nichrome.

Fig. 3.

per cent. of silicon, has a Hall effect about 75 per cent. greater than that in electrolytic iron and about 10 per cent. greater than that in Kahlbaum iron. The further addition of silicon causes a rapid increase in the Hall effect so that Steel I. which contained 3.80 per cent. silicon gives a Hall effect about sixteen times that in Kahlbaum iron. On the other hand the addition of silicon to the iron causes a decrease in the temperature coefficient of the Hall effect. The direction of the Hall effect in each of these steels is the same as its direction in pure iron. Table I. gives the values of R calculated from the equation,



Hall Effect in Silicon Steels.

Fig. 4.

$$E = \frac{RHI}{d},$$

where E, H, and I are in absolute units and d in centimeters. In this table is also included the thermoelectromotive forces against copper. The first addition of silicon causes a decrease in the thermoelectromotive force and further addition of silicon causes a reversal. With this reversal of the thermoelectromotive force there is not associated a reversal of the Hall effect.

TABLE I.

Name.	**Temp. ° C.**	*H.*	$R\times 10^8$.	**Thermo-electric Height 0°-100°.**
Monel	25°	1,650	− 35.1	$+22.9\times 10^{-6}$
	66°	1,650	24.2	
	96°	3,150	9.62	
	137°	5,300	2.38	
Nichrome	17°	3,300	+199	$+0.699\times 10^{-6}$
	120°	3,300	209	
	198°	1,050	200	
	216°	1,050	113	
	246°	3,300	21.2	
	286°	5,550	8.6	
Steel I	19°	6,000	+152	$+12.4\times 10^{-6}$
	130°	6,000	175	
	244°	6,000	208	
	310°	6,000	226	
Steel II	19°	6,000	+151	$+12.67\times 10^{-6}$
	128°	6,000	171	
	247°	6,000	199	
	311°	6,000	218	
Steel III	18°	7,100	+ 11.5	-6.54×10^{-6}
	129°	7,100	23.4	
	235°	7,100	44.3	
	307°	7,100	62.3	
Kahlbaum iron	17°	6,000	+ 10.8	-9.71×10^{-6}
	132°	6,000	22.4	
	250°	6,000	42.4	
	321°	6,000	61.2	

NERNST EFFECT IN MAGNETIC ALLOYS.

A study of the variation of the Nernst effect with temperature has already been made in nickel and cobalt. It was also desirable to have data on the Nernst effect in the alloys which have been studied in the earlier part of this paper with respect to the Hall effect. The thickness of the monel was 0.148 cm. The other plates were those used in the study of the Hall effect. The apparatus was essentially that used for the determination of the Nernst effect in nickel and cobalt, so that reference will be made to that paper[1] for the details of the experiment.

In Fig. 5 the Nernst electromotive forces in monel have been plotted against the magnetic fields; in Fig. 6, the corresponding values for nichrome. In Fig. 7 have been given the Nernst electromotive forces in the silicon steels when one end of the plate was at about 20° C. and the

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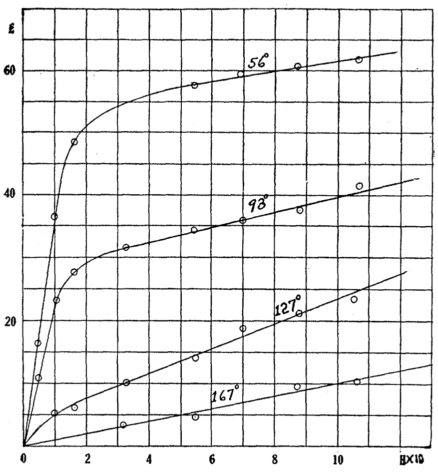
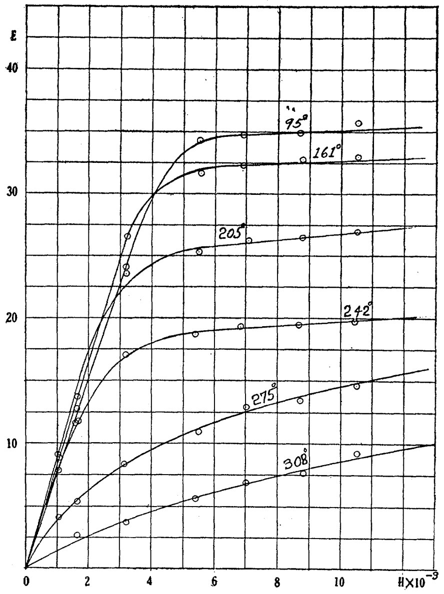
[1] Phys. Rev., 33, pp. 295–306, 1911.

other at the temperature of steam. The electromotive forces plotted for abscissæ in each of these figures have been reduced to the case that the flow of heat occurs in a plate one centimeter wide with a temperature gradient of 1° C. per centimeter in it. These curves are very similar to the corresponding curves for the Hall effect. There is at the low temperatures the initial proportionality between the electromotive force and the magnetic field with the characteristic bend in the region of saturation and then the gradual increase in the electromotive force with further increase in the magnetic field. Also a rise in temperature causes a decrease in Nernst effect except in the case of nichrome where for fields less than 3,000 C.G.S. units it increases slightly between 95° and 205° C. This is essentially the exception noted for the Hall effect. In the neighborhood of 167° C. for monel and 300° C. for nichrome these alloys seem to become non-magnetic and the Nernst electromotive force becomes proportional to the magnetic field. The direction of the effect in monel, nickel and nichrome is the same. From Fig. 7 it appears that steel containing 0.25 per cent. of silicon has a Nernst effect which is about one half of that in pure iron. The direction of the effects in the two cases is the same. The Nernst effect in steel containing 3.8 per cent. of silicon is opposite in direction to that in iron and about three and one half times as large. The addition of small amounts of silicon to the iron



Nernst Effect in Monel.

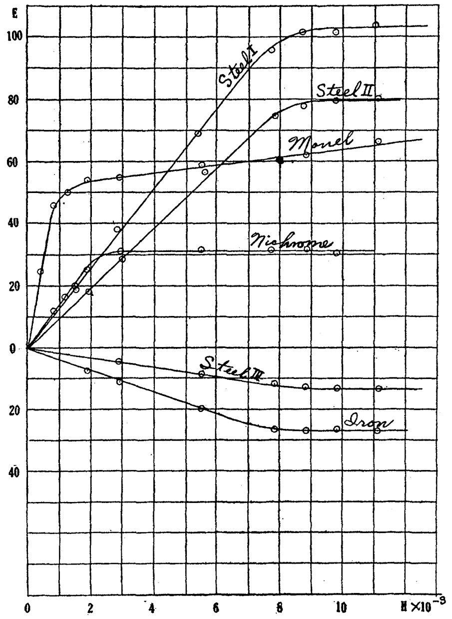
Fig. 5.



Nernst Effect in Nichrome.

Fig. 6.

causes the Nernst effect to decrease. The addition of larger amounts causes the effect to reverse its direction and to rise to a value much larger than that in pure iron. In the case of the Hall effect the addition of silicon to the iron caused an increase in the Hall effect but not a reversal of sign. The reversal of the thermoelectromotive forces occurs under the conditions under which this reversal of the Nernst effect occurs. If the Nernst effect is regarded as the rotation of the thermoelectromotive force in the plate the Nernst effect and the thermoelectromotive force should reverse simultaneously. This is exactly what happens in these alloys.



Nernst Effect in Silicon Steels.

Fig. 7.

Table II. contains the values of Q calculated from the equation,

$$E = Q\beta H \frac{\partial T}{\partial x},$$

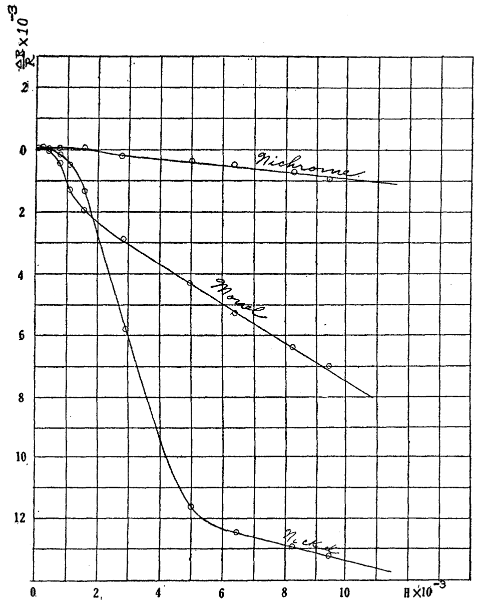
where E is the electromotive force in absolute units; H, the magnetic field in absolute units; β, the width of the plate in centimeters, and $\frac{\partial T}{\partial x}$, the temperature gradient in degrees Centigrade per centimeter.

TABLE II.

Name.	Temp. ° C.	H.	$Q \times 10^2$.	Thermo-electric Heights 0°–100°.
Monel	56°	1,500	−32.3	$+22.9 \times 10^{-6}$
	93°	1,050	22.1	
	127°	1,000	5.3	
	167°	1,060	.97	
Nichrome	43°	2,500	− 7.08	$+ 0.699 \times 10^{-6}$
	95°	3,200	7.53	
	161°	3,250	8.12	
	205°	1,650	7.70	
	242°	1,650	7.00	
	275°	1,650	3.27	
	308°	7,000	.99	
Steel I	38°	15,400	− 6.19	$+12.4 \times 10^{-6}$
Steel II	33°	14,000	− 4.85	$+12.67 \times 10^{-6}$
Steel III	41°	15,600	+ 0.72	$- 6.54 \times 10^{-6}$
Iron	47°	15,600	+ 1.71	$- 9.71 \times 10^{-6}$

TRANSVERSE CHANGE OF RESISTANCE IN A MAGNETIC FIELD.

The wires were wound on thin sheets of mica as nearly as possible plane. The nickel wire which was from Hartmann and Braun was 0.030 mm. in diameter. The monel and nichrome wires were 0.075 mm. in



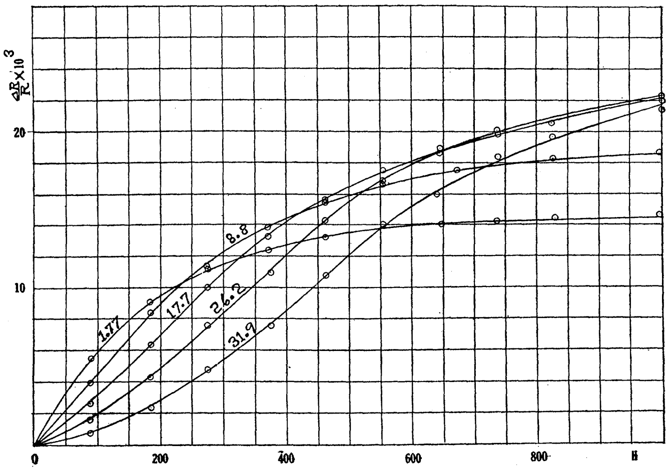
Transverse Change of Resistance in Monel, Nichrome and Nickel.

Fig. 8.

diameter. The coils were placed between the poles of a large electromagnet so that the lines of force were as nearly as possible normal to the plane of the coil. Necessary precautions were taken concerning temperature equilibrium. The observations on three coils at room temperature are recorded in Fig. 8. The slight increase in resistance for lower fields has been attributed to the failure to get the coil perfectly plane and exactly perpendicular to the lines of force so that there is superposed on the transverse change of resistance a longitudinal change arising from the component of the field parallel to the plane of the coil. The longitudinal change of resistance is an increase and for these small fields exceeds the transverse change. The transverse change of resistance in nichrome is small compared to that in nickel, and that in monel for fields greater than about 3,000 C.G.S. units is roughly one half the change in nickel.

Influence of Tension on the Longitudinal Change of Resistance.

It has been shown by Williams[1] that nickel wires sustaining different tensions give different values for the longitudinal change of resistance in a magnetic field. A similar series of observations has been made on monel and for the sake of comparison nickel has been again studied. The monel wire was hung so as to coincide with the axis of a large vertical solenoid about one meter in length. The monel wire was about 80 cm. long and 0.0254 cm. in diameter. The solenoid was provided with a water jacket between the magnetizing coil and the space containing the



Longitudinal Change of Resistance in Nickel for Different Loads.

Fig. 9.

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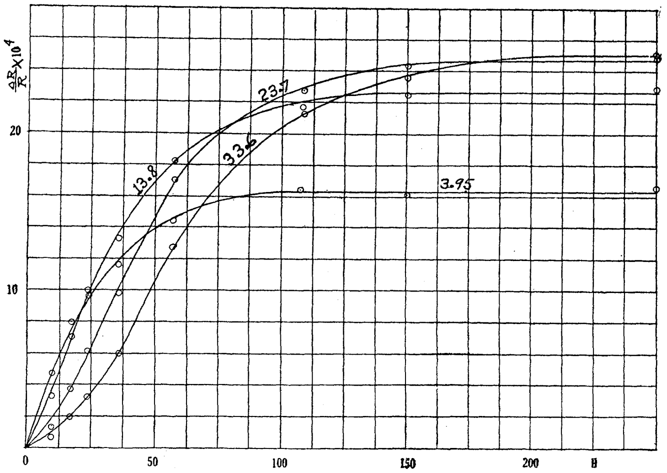
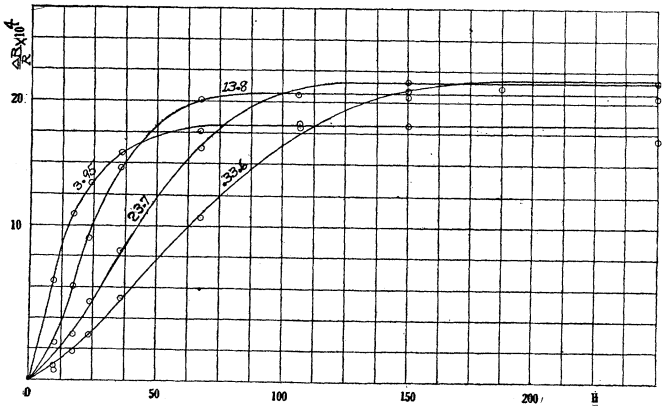
[1] Phil. Mag. (6), 6, p. 693, 1903.

wire to be studied. Further insulation from temperature changes was afforded by filling the space between the inner wall of the water jacket and the wire with cotton wool. The tensions were obtained by hanging different weights on the wire. The resistances of the wire at room temperature for different fields and different loads were measured. The wire was demagnetized after each observation. The tensions expressed in kilograms per square millimeter have been indicated on the curves in the figures. For the study of the nickel wire a more powerful solenoid was used. It was 46 cm. long. The nickel wire was .0425 cm. in diameter and 25 cm. long. In order to have a greater length of wire two



Longitudinal Change of Resistance in Unannealed Monel for Different Loads.

Fig. 10.



Longitudinal Change of Resistance in Annealed Monel for Different Loads.

Fig. 11.

wires parallel to each other and near together were joined in series by soldering the lower end of each one to a heavy strip of copper to which the weights affording the tension were attached. These wires were then placed in the solenoid so that the axis of the solenoid was between them. Fig. 9 gives the results for an annealed nickel wire; Fig. 10, for the monel wire before annealing; and Fig. 11, for the monel wire after annealing. For small tensions the change of resistance rises rapidly to its limiting value beyond which it does not increase with further increase in the magnetic field. The increase in the tension makes this rise to the limiting value less rapid and at first increases the magnitude of the limiting value but for tensions exceeding a certain value of the change of resistance for the larger magnetic fields seems to be the same whatever the tension. Annealing the monel makes the influence of tension greater at lower fields and less at larger fields. The results for monel are exactly similar to those for nickel except that smaller fields are required to reach the limiting value in monel than in nickel.

Influence of Occluded Hydrogen on the Hall Effect in Palladium.

It is well known that palladium when made the cathode is an electrolytic cell in which the positive current is carried by hydrogen occludes large quantities of hydrogen, so that when saturation has been reached the palladium is found to contain a quantity of hydrogen which at atmospheric pressure would be equal to more than one thousand times its own volume. A number of observers have shown that this occluded hydrogen causes the electrical resistance[1] to increase. This increase of resistance is approximately proportional to the quantity of hydrogen occluded. When saturation is reached the resistance is about 68 per cent. greater than that in palladium free from hydrogen.

In order to study the Hall effect in palladium which contained occluded hydrogen, plates 1.2 cm. wide and 2.5 cm. long were cut from a sheet of palladium 0.03 cm. thick. From the middle of either side of the plate projected arms to which were soldered or welded palladium wires which lead to the galvanometer leads. These Hall electrodes were adjusted so as to be nearly on the same equipotential. To the ends of the plates were soldered heavy strips of copper which served as primary electrodes. The plate was mounted on a sheet of mica from which a rectangular opening had been cut so that both sides of the plate were exposed. The leads to the plate were encased in small rubber tubing and the copper parts covered with wax to protect them from the acid. The plate was

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[1] McElfresh, Proc. Amer. Acad., 39, p. 323, 1904.

then mounted on a frame midway between two platinum plates which were parallel to it. These platinum plates were much larger than the palladium plate. They were joined in multiple and served as the anode of the electrolytic cell. The electrolyte was a seven per cent. water solution of sulphuric acid. When the palladium plate was in position in this cell the current flowed from the platinum plates to either side of the palladium plate so that hydrogen would be deposited at the same rate on either of the faces. Over the palladium plate in such a way as to collect the hydrogen evolved at it, was an inverted burette to which had been joined a funnel. In series with this electrolytic cell was an ordinary hydrogen voltameter with platinum electrodes. The difference between the quantity of hydrogen generated in this voltameter and the quantity generated at the palladium electrode gave the quantity of hydrogen absorbed by the palladium.

The Hall effect was first determined in the plate in the usual way when the plate was free from hydrogen. The intensity of the magnetic field was 20,300 C.G.S. units and the observations were made at room temperature. The plate was then placed in the electrolytic cell and the current allowed to flow until the plate had absorbed about one thousand times its volume of hydrogen. The Hall effect in the plate was again determined. Two plates cut from the same sheet of palladium were examined. In the first of these, the palladium lead wires were soldered to the Hall electrodes; in the second plate they were welded. The second plate gave less trouble on account of thermoelectromotive forces, so that the results for it are more accurate than those for the first plate. Within the error of observation, which did not exceed two per cent. for the first plate and one per cent. for the second plate, there is no change in the Hall effect caused by the occlusion of the hydrogen. Table III. gives the results for the two plates.

TABLE III.

	Current in Amps.	Thickness in Cm.	R before Saturation with H.	R after Saturation with H.
Plate I..................	4.50	0.0309	7.69×10^{-4}	7.54×10^{-4}
Plate II.................	4.45	0.0305	7.54×10^{-4}	7.49×10^{-4}

In consideration of the change of electrical resistance under analogous conditions, this result was scarcely to be expected. Work on the Hall effect in alloys indicates that alloys with high electrical resistances have large Hall effects. The occlusion of hydrogen, however, does not change the electrical resistance and the Hall effect in the same manner. If the Hall effect depends on the mean free path of the electrons, the occlusion of such a large quantity of hydrogen would be expected to change its magnitude.

Hall Effect and Polymorphism of Tellurium.

From a study of the thermoelectromotive force and the electrical resistance of tellurium Haken[1] has concluded that tellurium exists in two crystalline forms. One of these forms seems to be stable above 350° C.; the other, stable below that temperature. It seemed that the study of the variation of the Hall effect with the temperature might give additional evidence of this polymorphism.

The tellurium was obtained from Kahlbaum. The plates were cast by heating the metal in a crucible and pouring it into a mould cut out of lavite. These plates were about 4 cm. long, 1.4 cm. wide and 0.3 cm. thick. From the middle of either side projected an arm about 1 cm. long and 0.4 cm. wide. These arms when fastened to the wires leading to the galvanometer served as the secondary or Hall electrodes. Either platinum or silver wires were fastened to the plate at the primary as well as at the secondary electrodes. The temperatures which were obtained by means of an electric furnace were measured with a platinum platinum-irridium thermal couple. The magnetic field had a strength of 8,800 absolute units. It was found that the way in which the plates were cooled and the heat treatment to which they were afterward subjected very largely changed the value of the Hall constant at room temperature. At higher temperatures the variations from this cause were not so large. The character of the curve showing the relation between the Hall constant and the temperature remained essentially the same whatever the heat treatment or the condition of cooling.

A number of plates were investigated. The values of the Hall constants obtained for two of these plates have been given in Table IV. and the same values have been plotted in Fig. 12. The plates for which these values are given were cast as nearly as possible in the same way by pouring the moulten tellurium into the mould at room temperature. The observations here tabulated are those made on the first heating of the plate from room temperature to the highest temperature indicated on the curve. The points on the curve marked with a circle refer to Plate I. and those marked with a circle and a cross refer to Plate I. A single curve has been drawn for both sets of points, although two curves, one lying a little above the other would better represent the facts. From this curve it is seen that with rising temperature the Hall effect in tellurium decreases very rapidly until 180° C. is reached. Between 180° and

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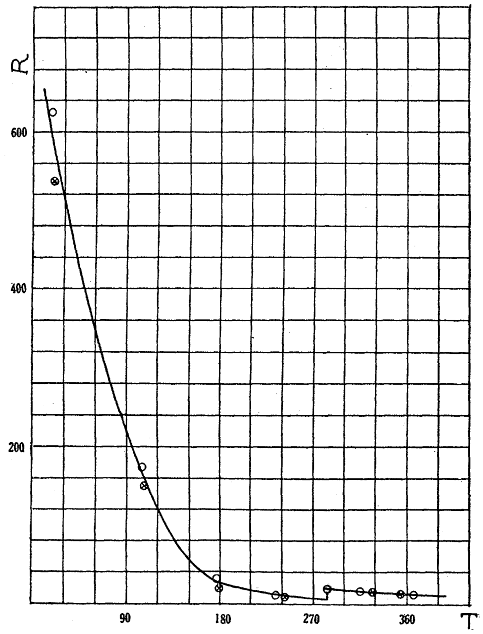
[1] Ann. d. Phys. (4), 32, p. 291, 1910.

TABLE IV.

Plate I.		Plate II.	
Temp. C °.	*R*	Temp. C °.	*R*
21.8	536	20.3	621
109	147	105	171
180	18.8	177	30.5
243	7.47	234	8.96
283	18.0	283	19.3
327	14.9	315	18.1
353	12.0	366	12.5



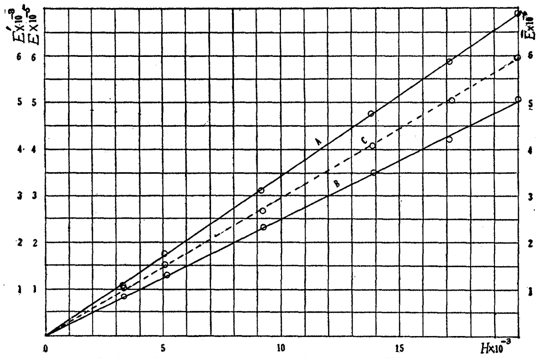
Hall Effect in Tellurium.

Fig. 12.

about 275° C. the effect decreases slowly. In the neighborhood of 275° C. a molecular transformation occurs in which the Hall constant is doubled. With further rise of temperature the constant decreases slowly as compared to the decrease at lower temperatures. From room temperature up to about 275° C. the tellurium is evidently a mixture of the two crystalline forms. One of these forms will be in unstable equilibrium. The relative concentrations of these crystalline forms will vary as the temperature is changed. In the neighborhood of 275° C. one of these crystalline forms goes over into the other and there remains a single crystalline form in which the Hall effect behaves as in non-magnetic metals. These results on the Hall effect in tellurium confirm the results of Haken that tellurium exists in two crystalline forms. The temperature at which this molecular transformation occurs as indicated by the Hall effect does not agree very well with the temperature at which Haken found the behavior of the thermoelectromotive force and the electrical resistance indicated a molecular transformation.

The Hall Effect in Iron Pyrites and Galena.

Very little is known concerning the Hall effect in crystals. This lack of information is largely due to the difficulty in securing suitable crystals from which to cut plates adapted to the study of this effect. It was, however, found possible to obtain a plate of iron pyrites and two plates of galena in which the Hall effect could be observed. The crystal of iron pyrites was a large unmodified cube from which was cut a plate in such a way that its plane was parallel to one of the faces of the cube. This plate was 2.2 cm. long, 1.1 cm. wide and 0.18 cm. thick. Galena also crystallizes in the isometric system and each of these plates was cut so that its plane was parallel to one of the faces of the crystal. One of these plates was 1.5 cm. long, 0.8 cm. wide and .30 cm. thick; the other was 2.0 cm. long, 0.8 cm. wide and 0.303 cm. thick. The ends of the plates were copper plated in order to make it possible to solder wires to them for the primary electrodes. In the middle of each side of the plates a small region was also electroplated. At these points were soldered the wires which served as the secondary electrodes. The observations were made in the usual way.



Hall Effect in Iron Pyrites and Galena.

Fig. 13.

Fig. 13 shows the results of these observations. In this figure the magnetic field in absolute units has been plotted for abcissæ and the electromotive force which would be observed in a plate one centimeter thick with a current of one absolute unit in it, has been plotted for ordinates.

Curve C is for iron pyrites. The ordinates for this curve are on the extreme left and have been denoted by E'. Curve A is for the first specimen of galena and curve B for the second specimen of galena. The ordinates of the former denoted by E are on the left; the ordinates of the latter on the right. These curves show that the Hall electromotive force for iron pyrites and galena is proportional to the magnetic field. At room temperature $R = -0.296$ for iron pyrites; $R = -34.2$ for first specimen of galena; and $R = -251$ for second specimen of galena. The negative sign means that the effect in these crystals has the same direction it has in bismuth. These crystals like bismuth are thermoelectrically negative with respect to copper. From the approximate relation between the thermoelectric series and the Hall effects, the Hall constant in these crystals would be expected to have the sign it has in bismuth.

SUMMARY.

1. An increase of temperature causes changes in the Hall effect and in the Nernst effect in monel and nichrome which are very similar to the changes produced in nickel, iron and cobalt under corresponding conditions.

2. The Nernst effect and the Hall effect in monel and in nichrome depend on the temperature in essentially the same way.

3. The addition of small quantities of silicon to iron causes a large increase in the Hall effect and a decrease in its temperature coefficient. Under similar conditions there is at first a decrease in the Nernst effect, then a reversal of its direction and an increase to a larger value in the opposite direction. Associated with this reversal of the Nernst effect is the reversal of the thermoelectromotive force against copper.

4. In a transverse magnetic field the resistance of monel and nichrome behaves like the resistance of nickel except that the changes under corresponding conditions are less than in nickel.

5. The influence of tension on the longitudinal change of resistance in a magnetic field in monel and in nickel is the same except for magnitude

6. Large quantities of occluded hydrogen do not change the Hall effect in palladium.

7. In the neighborhood of 275° C. there is a molecular transformation in tellurium. The Hall effect after this transformation is about double its value before this transformation.

8. The Hall effect has been determined in iron pyrites and galena. In these crystals the Hall electromotive force is proportional to the magnetic field.

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