A STUDY OF THE JOULE AND WIEDEMANN MAGNETOSTRICTIVE EFFECTS IN STEEL TUBES.

By S. R. Williams.

In 1842 Joule[1] discovered that an iron rod changed its length when subjected to a magnetic field whose direction was parallel to the axis of the rod. This variation in length with change in magnetic field strength was found to be an increment up to a certain value of the magnetic field beyond which the rod appeared to contract. Later investigators[2] showed that if sufficiently strong magnetic fields were used the bar actually became shorter than when in its virgin state.

Some years before this interesting discovery of Joule, Wiedemann[3] found that "if a vertical wire is magnetized with its south end uppermost, and if a current is then passed downwards through the wire, the lower end of the wire, if free, twists in the direction of the hands of a watch as seen from above, or in other words, the wire becomes twisted like a right-handed screw if the relation between the longitudinal current and the magnetizing current is right-handed.

"In this case the magnetization due to the action of the current on the previously existing magnetization is in the direction of a right-handed screw around the wire. Hence the twisting would indicate that when the iron is magnetized it expands in the direction of magnetization and contracts in directions at right angles to the magnetization. This agrees with Joule's results." Thus Maxwell[4] explains the phenomenon in his second edition of Electricity and Magnetism and I have quoted directly because in the first edition it is stated oppositely and some of our recent[5] writers have persisted

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[1] Joule, Phil. Mag. (37), vol. 30, pp. 76–225, 1847.

[2] Bidwell, Proc. Roy. Soc., 38, p. 265, 1885; 40, p. 109, 1886. More, Phil. Mag., 40, p. 345, 1895. Nagaoka, Rapports, Congress Internat. de Physique de 1900.

[3] Wiedemann, Elektricität, Bd. 3.

[4] Maxwell, Electricity and Magnetism, 2d ed., vol. 2, p. 87.

[5] Auerbach, Winkelmann's Handbuch der Physik, Elek. u. Mag., 2.

in giving the direction of rotation as Wiedemann[1] gave it originally, which is also incorrect.

Nagaoka and Honda[2] in their exhaustive studies on magnetostrictive effects in iron, nickel and cobalt, have indicated the direction of rotation even more correctly when they say: "The direction of twist in iron, so long as the longitudinal magnetizing field is not strong, is such that if the current is passed down the wire from the fixed to the free end and the wire is magnetized with north pole downwards the free end, as seen from above, twists in the direction of the hands of a watch." That is to say, if one increases the longitudinal magnetizing field from zero up to about three hundred units, c.g.s., the *initial* twist of the rod will be as Nagaoka and Honda have indicated, *viz.*, clockwise; but when the field strength reaches a value between 15 and 30 units a maximum twist in this direction occurs beyond which the twist appears to take place counter clockwise, *i. e.*, in the opposite direction and in a sufficiently strong longitudinal field the twist actually carries the scale reading to the opposite side of the zero point from that on which the maximum twist occurred. It is here perhaps that much of the confusion occurs. For instance, if a strong longitudinal field be imposed suddenly upon the iron bar, instead of gradually increasing it from zero up to that value, the twist will appear to occur counter clockwise, when the directions of the two fields are in a right-handed relation. In throwing on a strong longitudinal field it must necessarily build up from zero but occurring in such a short time the rod, due to inertia effects, does not twist to its maximum value but takes a mean position and then twists from that position to the one it holds for the maximum longitudinal field which gives it the appearance of twisting counter clockwise. I mention this question of direction of twist at some length because of the apparent confusion, when in reality there is none if we are careful to state what the magnitude of the longitudinal field is and whether the longitudinal field is suddenly or gradually built up. We must also keep in mind that the above holds for iron. In nickel the initial twist takes place in just the opposite direction and if we accept Maxwell's

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[1] Wiedemann, Die Lehre vom Galvanismus, Bd. 2, p. 256, 1873.

[2] Nagaoka and Honda, Phil. Mag., 4, p. 61, 1902.

explanation that the Wiedemann effect is a special case of the Joule, then this is what we would expect, as a nickel rod shortens[1] in the Joule effect instead of lengthening as iron does for small magnetic fields.

This paper has for its object the study of these two effects (the Wiedemann and the Joule), in the same samples of steel tubing. So far as the author knows little or no comparative work has been done on the same specimens. In the Wiedemann effect the use of steel tubes enables one to thread an insulated copper wire through the tube so that the current for producing the circular field could be sent either through the wire or the tube itself as a conductor. Both cases were studied. With the current insulated from the tube, the circular field can be more readily calculated, for as Knott[2] points out we know nothing of the distribution of the circular magnetic field inside a solid iron conductor through which a current is flowing.

DESCRIPTION OF APPARATUS.

In Fig. 1 is shown a diagram of the apparatus as used in this work. C is the magnetizing coil, T, the steel tube with an insulated wire running through the center, X_1, the reversing switch for the current which flows through the steel tube, $Am.$, R_1, the ammeter and resistance in series with the circuit. For controlling the current in the solenoid, C, a reversing switch, X, was connected in series with a variable resistance, R, and ammeter, $Am.$, and a double pole double throw switch, D, whereby either alternating or direct current could be passed through C. The alternating current was used for demagnetizing the steel tubes before each set of readings. The switch, S, served as a short circuit for the ammeter when the alternating current was used. M is a tube containing mercury to serve as a connection for the lower free end of the steel tube and the wire running through them. With this arrangement of circuits the direction of the longitudinal and circular fields could be varied at will and any desired combination used in the Wiedemann effect.

The ammeters were calibrated from time to time by means of

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[1] Barrett, Nature, 26, p. 585.

[2] Knott, Trans. Roy. Soc. Edinb., XXXII. (1), p. 193, 1883; XXXV, (2), p. 377, 1899; XXXVI. (2), p. 485, 1891.

a Leeds and Northrup potentiometer. The variable resistance, *R*, was a water resistance and was most satisfactory where one desired to vary the magnetic field continuously without any steps.

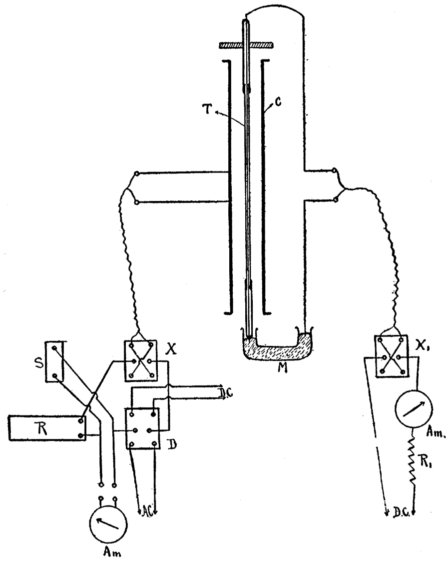

Fig. 1.

I am indebted to the Phœnix Physical Laboratory of Columbia University for the use of the solenoid, *C*, and wish hereby to express my appreciation of their kindness in loaning it. The coil is 100 cm. in length and wound in eight layers with 6,025 turns in all. It is wound on a very thick-walled brass tube with a slit running the full length of it. This thick-walled tube insured greater rigidity and also cut down heat changes in the space where the tubes were suspended.

I am particularly indebted to the Ellwood Ivins' Tube Works[1] for the excellent specimens of seamless steel tubing which they furnished me. There were four different sizes all of which were, according to manufacturers' notation, called "low carbon steel." For convenience I have designated these specimens, tubes *A*, *B*, *C* and *D* respectively. Their dimensions are as follows:

TABLE I.

Tube *A*.	Outer diameter,	.1600 cm.	Tube *C*.	Outer diameter,	.2447 cm.
	Inner diameter,	.0794		Inner diameter,	.0970
	Length,	79.8		Length,	79.7
Tube *B*.	Outer diameter,	.2386	Tube *D*.	Outer diameter,	.2088
	Inner diameter,	.1538		Inner diameter,	.1085
	Length,	80.2		Length,	80.0

The ends of the tubes, as the table indicates, were ten centimeters inside of the ends of the solenoid which gave fairly uniform fields.

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[1] Address: Oak Lane Station, Philadelphia, Pa., U. S. A.

Heavy brass tubing was brazed to the ends of the steel tubes for supporting them and making connections. The tubes were suspended vertically in the solenoid and carefully placed along the axis of the same. The support for the tube was independent of the solenoid. A tripod support which rested directly upon the upper end of the solenoid was first tried but the results were very discordant until the supports for the tubes and solenoid were made independent. The whole system of supports was rigidly attached to a thick stone wall of the laboratory.

For a study of the Joule effect the mercury tube, *M*, Fig. 1, was removed and in its place was used a system of levers, shown in Fig. 2, for measuring the changes in length of the tubes. *LL'* is a light lever of which *L* is the fixed end. *T* is a continuation of the tube which supports the lever at *B* in a stirrup while *S* is the solenoid. At *L'* a silk cord drops downward and coils several times around a small roller to which is attached a mirror, *M*, for reading the deflection by means of a telescope and scale. A small weight, *W*, keeps the silk cord stretched. The multiplying power of the levers was determined by attaching the table of the dividing engine to the point, *B*, and obtaining the deflection of the mirror when *B* was displaced through a measured distance. The multiplying power was found to be 11,935. This system of levers worked very satisfactorily and would return to its old zero point after the demagnetization of the tubes. Attention is called to the roller on which the mirror was mounted. It had "agate" bearings which may be made in any laboratory. A piece of capillary tubing was broken off squarely and heated in a Bunsen flame until the end was thoroughly fused and the capillary opening commenced to close. At this point it is taken from the flame and the other end treated in the same way. These fused ends of the capillary tubes make excellent bearings

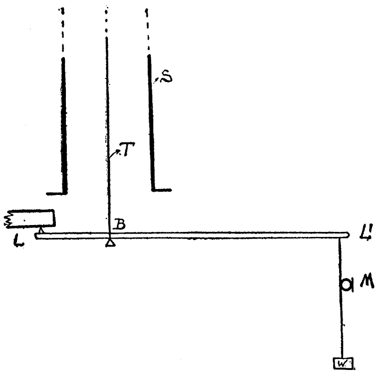

Fig. 2.

on steel needle points and have very small friction. The capillary tube may be used as a roller itself or short pieces of the tubing may be set into the ends of larger metallic cylindrical rods. In this work the glass tips were set in the end of a brass rod which was turned down to a small diameter where the cord passed around it. Fig. 3 shows more distinctly how it worked when supported by steel points.

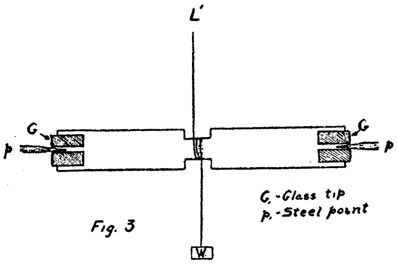

Fig. 3.

Methods of Observation.

In all of the specimens the following order of measuring the various tabulated results was used. First, the Wiedemann effect, second, the Joule effect, third, the permeability, fourth, the moments of torsion.

The values for the Wiedemann effect were obtained by keeping the current, producing the circular field, constant and by varying continuously the longitudinal field from zero up to the maximum value obtainable with the storage battery and coil which we have; this was about 275 c.g.s. units. The values thus obtained are the mean of four sets of readings taken in the following way:

Table II.

Vertical current flowing down.
Longitudinal field down.

Vertical current flowing up.
Longitudinal field down.

Vertical current flowing up.
Longitudinal field up.

Vertical current flowing down.
Longitudinal field up.

A reference to Fig. 1 will show that these various combinations were readily obtained by the connections and switches employed. The mean values thus obtained for the Wiedemann effect eliminated the action of the earth's magnetic field and also the dissymmetry of field in setting up the apparatus. Before taking each set of readings the tubes were demagnetized by passing a decreasing alternating current through the solenoid. At least the scale readings returned to zero each time after such a treatment. It is evident that heating the tubes each time for demagnetization was out of the question.

Several values for the vertical current were taken for each tube and these values were repeated when the vertical current flowed along the tube itself as a conductor and not in the wire inside of the tube.

It was found that the direction of the initial twist was always the same whether the circular field was applied first or the longitudinal, but that the twist was smaller if the longitudinal was applied first. Further the two fields were made to vary simultaneously from zero upward by connecting the solenoid and vertical wire in series; the initial twist still maintained the same relation to the two directions of the circular and longitudinal fields. The following table illustrates the relation of the circular and longitudinal fields and the direction of initial twist as viewed from upper end of tube.

TABLE III.

Circular Field.	Longitudinal Field.	Direction of Twist.
Current down.	Down.	Clockwise.
Current up.	Down.	Counter-clockwise.
Current up.	Up.	Clockwise.
Current down.	Up.	Counter-clockwise.

The direction of the field in the solenoid was determined by a compass needle and the direction of the current in the tube by applying the terminals of a milli-voltmeter to the terminals of the tube and also by the usual test of the compass needle in the neighborhood of a conductor.

The values for the Joule effect are the means of two sets of readings, first, when the longitudinal field was up; second, when the longitudinal field was down, demagnetization occurring between each set of readings. The field was varied continuously.

The permeability of the tubes was determined by the ballistic method and the results are the mean of several sets of readings.

The moments of torsion were determined in a torsion lathe. Two mirrors were attached to the tubes and the twist determined from the deflections of the mirrors as seen with two telescopes and scales. This eliminated any slipping at the chucks.

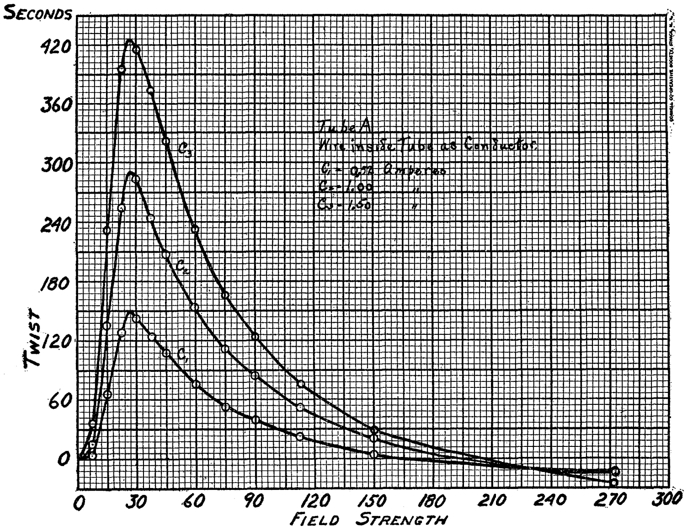

Fig. 4.

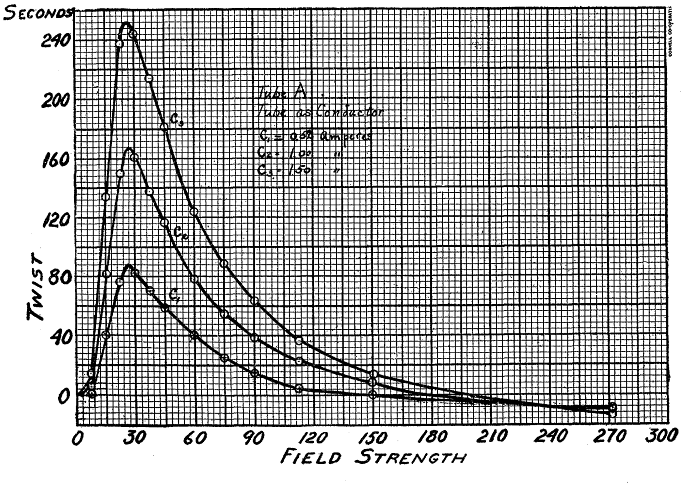

Fig. 5.

Table IV.

Tube A.

Longitudinal Field.	Total Twist of Tube in Seconds of Arc.						Total Lengthening in Centimeters.	Permeability.	Moment of Torsion.
	Vertical Current in Wire. Amperes.			Vertical Current in Tube. Amperes.					
	0.52	1.00	1.50	0.52	1.00	1.50			
	Twist.			Twist.					
0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
7.57	4.7	15.7	36.1	0.8	5.8	14.5	0.0	233.08	
15.14	66.3	135.5	231.8	40.0	81.2	134.2	7.46×10^{-7}	389.05	
22.71	128.4	254.1	395.6	76.1	149.2	237.5	———	443.98	
30.28	143.4	282.9	415.3	82.4	160.9	244.2	2.03×10^{-5}	409.09	615 gm. cm.
37.85	124.5	243.5	373.2	70.6	138.1	213.9	———	355.61	
45.42	108.0	209.0	322.1	59.6	116.5	180.2	2.61×10^{-5}	316.78	
60.57	76.6	154.4	232.5	40.0	78.5	125.6	2.82×10^{-5}	255.20	
75.71	53.8	111.9	167.7	25.5	55.7	89.1	2.82×10^{-5}	203.80	
90.85	39.2	84.4	123.7	15.7	39.2	63.6	2.82×10^{-5}	182.62	
106.00	———	———	———	———	———	———	———	161.74	
113.56	23.5	53.0	77.3	4.7	23.5	37.2	———	———	
151.42	4.7	21.5	29.4	0.0	8.6	13.7	2.73×10^{-5}	115.02	
272.56	–13.7	–13.7	–25.5	–8.6	–9.8	–13.7	2.06×10^{-5}	85.94	

Table V.

Tube B.

Longitudinal Field.	Total Twist of Tube in Seconds of Arc.						Total Lengthening in Centimeters.	Permeability.	Moment of Torsion.
	Vertical Current in Wire. Amperes.			Vertical Current in Tube. Amperes.					
	1.00	1.50	2.00	1.00	1.50	2.00			
	Twist.			Twist.					
0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	
7.57	53.0	57.1	113.3	4.8	14.8	18.9	0.00	706.32	
15.14	167.6	234.0	323.7	45.0	63.1	73.1	4.58×10^{-6}	739.40	
22.71	181.7	266.1	357.9	56.2	75.1	90.4	———	602.90	2,704 gm. cm.
30.28	170.8	246.0	333.6	56.2	73.1	91.2	1.36×10^{-5}	470.61	
37.85	150.7	217.9	293.5	51.0	69.5	82.4	———	390.64	
45.42	130.6	189.0	256.1	46.6	64.4	75.1	1.61×10^{-5}	329.31	
60.57	101.3	144.7	197.0	40.2	53.0	63.1	1.65×10^{-5}	267.38	
75.71	77.2	110.5	151.5	34.1	45.0	54.2	1.65×10^{-5}	219.87	
90.85	63.1	88.4	119.4	28.9	37.7	45.0	1.64×10^{-5}	190.41	
106.00	———	———	———	———	———	———	———	164.55	
113.56	44.2	63.1	84.4	18.9	30.9	34.9	———	———	
151.42	20.9	28.9	48.2	12.5	22.1	26.9	1.56×10^{-5}	120.66	
272.56	2.8	2.0	8.8	4.0	10.8	16.8	1.25×10^{-5}	82.18	

Tables IV., V., VI. and VII. give the various results for tubes *A*, *B*, *C* and *D* respectively, which are plotted in Figs. 4, 5, 6, 7, 8, 9, 10, 11 and 12. Fig. 4 shows the total twist for tube *A* when three different vertical currents were used and which flowed along the insulated wire inside of the tube. Fig. 5 represents the total twist

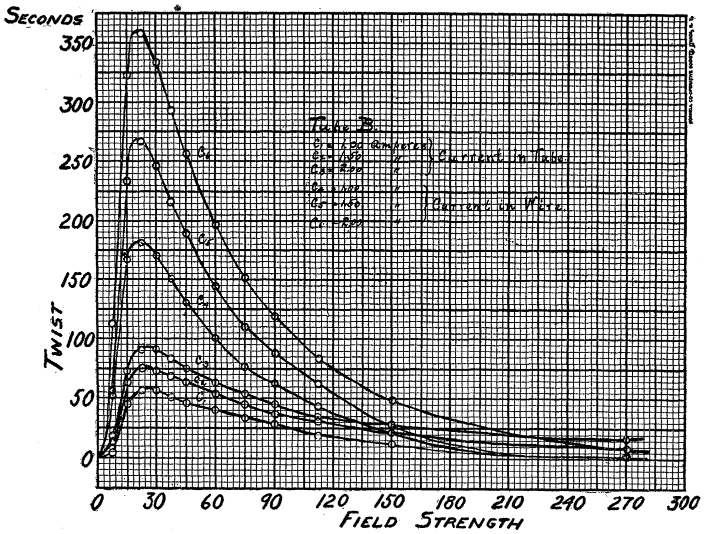

Fig. 6.

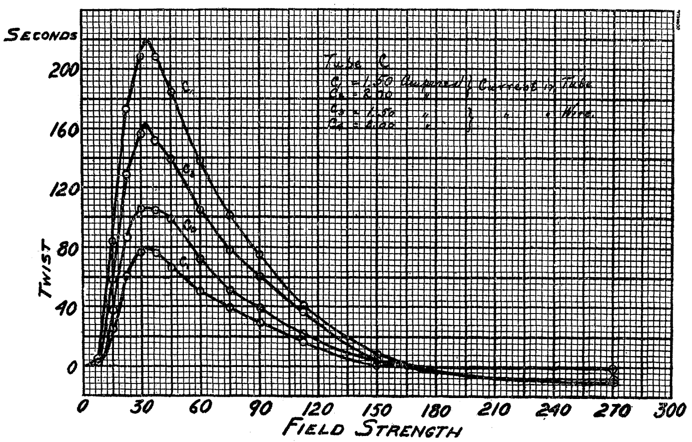

Fig. 7.

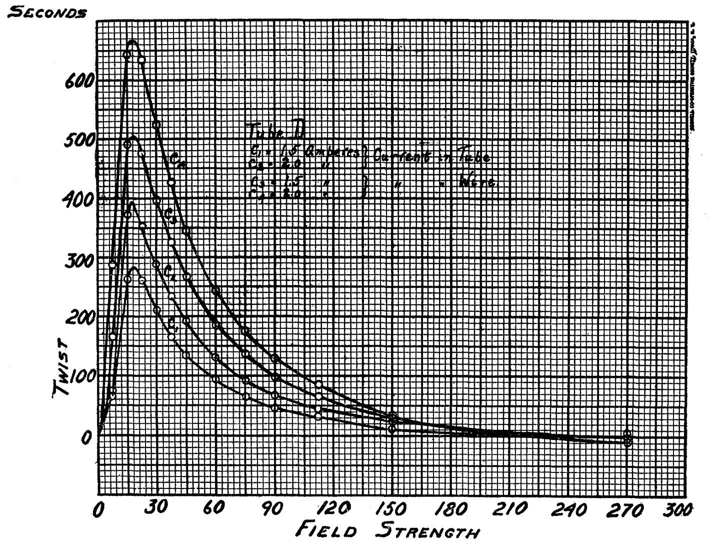

Fig. 8.

TABLE VI.

Tube C.

Longitudinal Field.	Total Twist of Tube in Seconds of Arc. Vertical Current in Wire. Amperes. 1.50 Twist.	Total Twist of Tube in Seconds of Arc. Vertical Current in Wire. Amperes. 2.00 Twist.	Total Twist of Tube in Seconds of Arc. Vertical Current in Tube. Amperes. 1.50 Twist.	Total Twist of Tube in Seconds of Arc. Vertical Current in Tube. Amperes. 2.00 Twist.	Total Lengthening in Centimeters.	Permeability.	Moment of Torsion.
0.00	0.0	0.0	0.0	0.0	0.00	0.00	3,504 gm. cm.
7.57	2.8	4.8	0.8	0.0	0.00	133.51	
15.14	58.8	84.1	24.8	38.0	0.00	381.69	
22.71	128.2	173.1	60.9	86.9	——	440.72	
30.28	156.3	208.4	76.1	106.2	0.53×10^{-5}	404.11	
37.85	151.1	208.4	76.1	105.0	——	362.56	
45.42	139.0	185.2	66.9	99.0	1.28×10^{-5}	322.15	
60.57	105.0	138.2	50.1	72.9	1.59×10^{-5}	265.30	
75.71	78.1	100.2	38.8	51.0	1.59×10^{-5}	220.98	
90.85	60.0	74.9	29.6	38.8	1.59×10^{-5}	191.58	
106.00	——	——	——	——	——	168.37	
113.56	36.8	40.0	16.4	22.0	——	——	
151.42	4.0	8.0	2.8	6.0	1.55×10^{-5}	120.83	
272.56	-8.8	-10.8	0.0	-0.8	1.34×10^{-5}	72.27	

for *A* when the same vertical currents as in Fig. 4 were used, only they flowed in the tube itself. Fig. 6 shows the same thing for tube *B*, the three upper curves for the case when the current is flowing in the wire inside of the tube and the three lower when the tube was the conductor. In all of the tubes the maximum twist was greater when the current was insulated from the tube than when flowing in the tube itself. Similarly Figs 7 and 8 show the total twist for tubes *C* and *D* respectively with the two upper curves for current in wire inside of tube and the two lower curves for the vertical current in the tube. Fig. 9 represents the total twist for the four tubes under exactly the same conditions. In these curves the vertical current was insulated from the tubes. Fig. 10 indicates the Joule effect for the four tubes under the same conditions. Figs. 11 and 12 show their permeability.

TABLE VII.

Tube D.

Longitudinal Field.	Total Twist of Tube in Seconds of Arc.				Total Lengthening in Centimeters.	Permeability.	Moment of Torsion.
	Vertical Current in Wire. Amperes.		Vertical Current in Tube. Amperes.				
	1.50	2.00	1.50	2.00			
	Twist.		Twist.				
0.00	0.0	0.0	0.0	0.0	0.00	0.00	1,876 gm. cm.
7.57	167.9	288.0	69.2	75.3	0.00	668.74	
15.14	490.2	642.6	263.8	372.6	0.31×10^{-5}	774.99	
22.71	477.3	634.5	262.6	352.5	———	631.90	
30.28	396.8	524.5	211.5	288.8	1.56×10^{-5}	506.04	
37.85	324.2	427.0	165.1	234.4	———	412.47	
45.42	266.6	347.2	135.7	192.1	1.69×10^{-5}	354.87	
60.57	186.1	241.7	92.6	130.9	1.68×10^{-5}	277.21	
75.71	136.9	175.2	65.2	91.4	1.65×10^{-5}	225.10	
90.85	99.5	129.7	47.1	69.2	1.63×10^{-5}	194.43	
106.00	———	———	———	———	———	167.49	
113.56	66.4	80.5	31.0	45.1	———	———	
151.42	30.2	34.2	10.8	26.1	1.51×10^{-5}	122.07	
272.56	–2.8	–8.8	–0.8	4.8	1.17×10^{-5}	81.94	

Discussion of Results.

In Figs. 9, 10, 11 and 12 are shown the lengthening and twist and permeability of the four tubes. It is interesting to note that the curves for lengthening and twist of the tubes *A* and *C* have this characteristic in common with the permeability curves that their maxima occur at a higher value of the longitudinal field than do those of the tubes *B* and *D*. Apparently the permeability is the

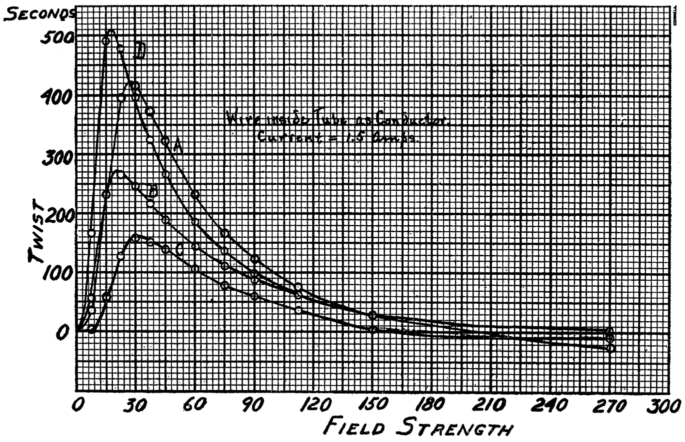

Fig. 9.

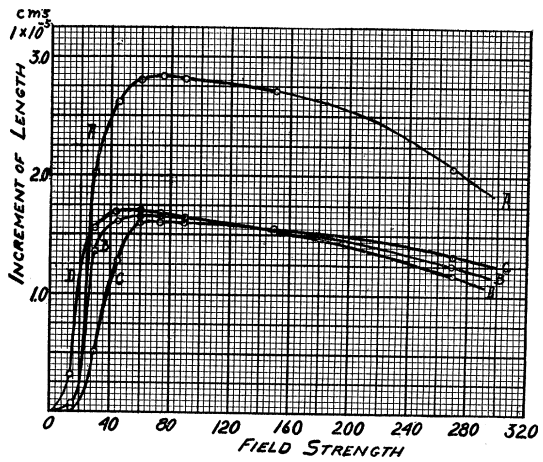

Fig. 10.

only property of the tubes which gives a decided color to the character of the curves of twist and lengthening. From the curves

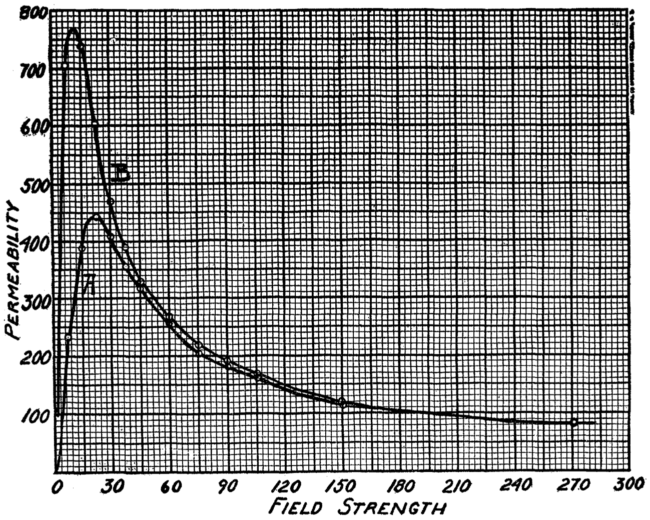

Fig. 11.

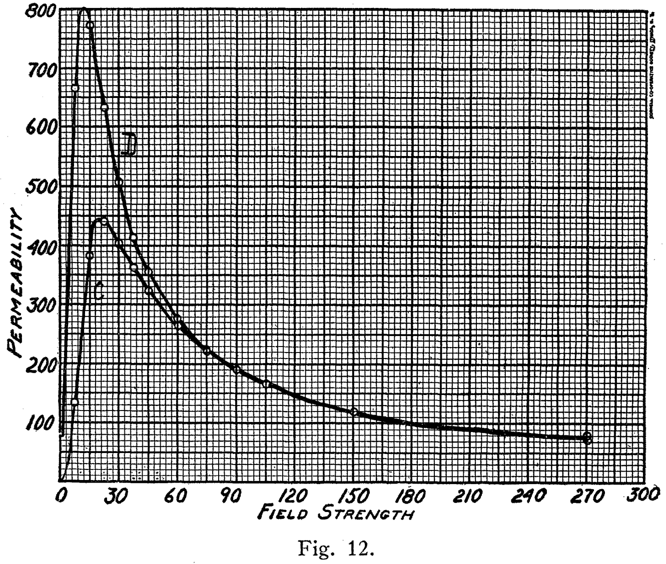

Fig. 12.

showing the Wiedemann and Joule effects it would also appear that the permeability influenced the twist more than the lengthening.

In no other way, it seems, can one account for the general results which I have tabulated in the following manner:

TABLE VIII.

Maximum twist,	$D > A > B > C$.
Maximum lengthening,	$A > D > B > C$.
Maximum permeability,	$D > B > A > C$.
Moment of torsion,	$A < D < B < C$.
Mean radius,	$A < D < C < B$.

From Maxwell's explanation one might be led to suppose that in the steel tube showing the maximum lengthening one would find a maximum twist. This does not hold for all of the tubes as shown by the curves for A and D. Their moments of torsion, mean radius and lengthening all indicate that A ought to twist more than D for a given torque, but such is not the case and although I repeated my results with numerous imposed conditions the relations still held. If the permeability is an important factor in the twist, we would expect D to twist more than A, since the maximum permeability of $D > B > A$. This reasoning however does not hold for tubes A and B when they are compared, but here either the moment of torsion or the mean radius at which the circular field is acting may be the important factor, as their difference in permeability is not as great as that of D and A. The results at least lead to the conclusion that there is no simple relation between the Joule and Wiedemann effects.

The comparative study of the twist in the Wiedemann effect when the vertical current is flowing in the wire and when flowing in the tube show that the maximum twist is from two to four times as great in the first case as in the second. I suppose this is to be ascribed to the fact that when the vertical current is flowing in the tube itself as a conductor there is not as large a circular magnetic field operative on the tube as when the same current is flowing in the wire, for there is no magnetic force in the interior of a cylindrical tube conveying a current.

As pointed out at the beginning, the use of tubes in the study of the Wiedemann effect offers some advantages over solid rods: first, one can determine the circular magnetic field when the current is confined to an insulated wire inside of the tube, secondly, for the same vertical current the Wiedemann effect is increased when the current flows in the wire.

For the tube *A*, the moment of torsion equals 615 gram-centimeters. The maximum twist for a vertical current of 1.5 amperes is equal to 415.3 seconds. This means that a torque of about 1.24 gram-centimeters would have been necessary to have produced the same twist. If we take as our mean radius of *A* a value of .06 centimeters it would mean a force of 20 + grams weight acting at that arm's length to produce the effect. It is interesting to consider in connection with this that due to the circular magnetic field about the vertical current that the lower free end of the tube, since it is a magnetic pole in the Wiedemann effect, tends to rotate about the current with a torque equal to $2mI$ where m equals the pole strength and I is the current. The direction of this torque would be that of the initial twist in the Wiedemann effect. Computing this for the case where the permeability is a maximum in the tube *A* shows that this torque has a value of only a few dyne-centimeters and hence may be neglected.

If the equipment had been available I would have preferred to have carried out these experiments on a much larger scale, *viz.*, by using tubes several meters long and consequently of larger diameters and corresponding solenoid for producing the longitudinal fields. Limited thus I present the results obtained from the equipment I had at my disposal.

Mr. Dorsey[1] in a recent article on the Joule effect gives an excellent bibliography of the subject; most of the articles referred to were available in this work.

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[1] Dorsey, PHYS. REV., vol. 30, p. 698, 1910.