X. *Effects of Stress and Magnetisation on the Thermoelectric Quality of Iron.*

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[Plates 21--23.]

§ 1. In May, 1881, the writer submitted to the Royal Society a paper entitled "Effects of Stress on the Thermoelectric Quality of Metals, Part I.," an abstract of which was published in the 'Proceedings,' vol. 32 (1881), p. 399. The paper was described as incomplete, and its further publication was postponed until additional results should be submitted. The experiments were continued in 1882–3, in the physical laboratory of the University of Tokiô, in conjunction with others on the magnetisation of iron. These latter, which were communicated to the Royal Society in January, 1885, and are now being published in the 'Philosophical Transactions,'* have a very intimate relation to the subject of this paper, and the writer has for this reason deferred the publication of the thermoelectric experiments until the appearance of the experiments in magnetism. The present paper embodies the results of the paper referred to above as Part I. (sufficiently fully to make separate publication of that part unnecessary), along with those of subsequent work, in which the writer has to acknowledge the very valuable help of one of his Japanese students, Mr. S. Sakai.

§ 2. In the earlier experiments the thermoelectric effects of stress on an iron wire were studied by exposing a piece of the wire to longitudinal pull, while one of the junctions between the stressed and the unstressed part was kept at a temperature of about 100° C., the other junction being at the atmospheric temperature, or about 15° C. to 20° C. The wire was held at one end of the stressed portion by being twisted round a fixed hook. Various plans of heating this junction were tried; the plan finally selected, and followed throughout all the experiments, was to immerse the hook in a bath of hot oil, whose temperature was kept very nearly uniform by a regulated flame under it. The other end of the stressed portion of the wire was connected to a cord which passed over a fixed pulley, and from which a light water-tank hung. Pull was applied to the wire by running water into the tank, and could be relaxed by allowing water to escape through a stopcock at the foot of the tank. Water was run in at a sensibly uniform rate, and the pull on the wire was given by

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* "Experimental Researches in Magnetism," Phil. Trans., vol. 176 (1885), p. 523.

the reading of a glass gauge-tube at the side of the tank, which was graduated to show each kilogramme of pull on the wire. In all the experiments described in Part I. the water-tank was used as the means of applying load; but in later work it was found more convenient, and not less satisfactory, to load the wire by stringing discs of lead on a vertical rod which took the place of the tank.

§ 3. The wire, which was a piece of moderately soft iron, was well annealed, to begin with, throughout its whole length by heating it to bright redness and allowing it to cool in the air. Its slack ends were soldered to copper leading wires, and these were connected to a mirror galvanometer whose resistance was 0·25 ohm. The effects of stress in altering the thermoelectric quality of the iron were measured by the deflection of the galvanometer, that being proportional to the electromotive force due to the difference of temperature of the two ends of the stressed part. This electromotive force was so small that the galvanometer required to be adjusted to a high degree of sensibility by using a controlling magnet to weaken very much the earth's directing field on the needle. In consequence of this the zero position of the needle became somewhat variable, and to eliminate error from this cause, double readings of the deflection were always taken by manipulating a reversing-key in the circuit. At the two copper-iron junctions a very slight difference of temperature would have given rise to an electromotive force greater than that which it was the object of the experiments to measure, and much care had to be taken to keep their temperature the same. They were immersed close together (but, of course, without contact) in a large beaker of paraffin oil, which was stirred from time to time, and was screened from radiation. In later experiments the value of the thermoelectric electromotive force was determined in absolute measure. In those, however, which have first to be described its value is stated only in the arbitrary unit which corresponds to one scale division of the galvanometer.

§ 4. The effect is called positive when the piece of iron affected has its thermoelectric position (with the assigned temperatures of the junctions) shifted towards bismuth in the thermoelectric series. In other words, the effect is called positive when it causes a current to pass from the part affected to the part unaffected through the hot junction.

The following (§§ 5–16) is a summary of the results stated in the paper referred to above as "Part I.," illustrated by figures taken from that paper.

§ 5. The first effects of loading are in many cases somewhat uncertain. This may be ascribed to the fact that continuous portions of any sample of wire differ more or less in thermoelectric quality, and the yielding which occurs during the first loading is apt to make some variation in the precise position along the wire of the hot junction. On the whole, however, the experiments agree in showing that the first effect of loading an annealed iron wire is *negative;* that is to say, if there is no current before the load is applied, the effect of a moderate amount of load is to make a current flow from the unstressed to the stressed portion of the wire through the hot junction.

This is in agreement with observations published as long ago as 1856 by Sir W. THOMSON, who has laid the foundation of the subject in Part III. of his great series of papers on the "Electrodynamic Qualities of Metals." (Phil. Trans., vol. 146 (1856), p. 709, or Reprint of Papers, vol. II.)

§ 6. If, however, the application of load be continued up to and beyond the limit of elasticity of the metal, the negative effect passes a maximum, becomes much reduced, and generally even changes to positive before the wire breaks.*

A characteristic example of this action is given in fig. 1, Plate 21, which shows the thermoelectric effect of loading an annealed iron wire up to the breaking point. The initial electromotive force (which has a small negative value) is due to accidental defect of homogeneity in the wire. The maximum negative E.M.F. is reached at or near the limit of elasticity (12 kilos.), and the subsequent drawing out is associated with a rapid change towards positive. After the wire was broken the load was removed, and the broken ends joined. A strong positive deflection then showed that the part which had suffered longitudinal strain, and was now freed from stress, was thermoelectrically positive to the other portions. This result has also been previously pointed out by Sir W. THOMSON † as well as by MAGNUS.‡

§ 7. Another experiment is given in fig. 2, where *a a* shows the effect of the first loading of another piece of annealed iron wire of larger section than the last. In this case the loading was stopped at 35 kilos., before the wire broke, and the load was gradually removed. The thermoelectric changes which took place during the removal are shown by the curve *b b*. During removal of load the E.M.F. again changed to negative, passed through a negative maximum, changed to positive, and finally, when the load was entirely removed, exhibited the positive value which MAGNUS and THOMSON have remarked.

The load was then gradually reapplied, and this resulted in the complex changes of E.M.F. shown by the curve *c c*—a curve by no means coincident with that found during the removal of the load. The loading was continued past 35 kilos. At 36 kilos. a sharp change of gradient occurred as the wire (hardened by the previous stretching) began again to draw. At 38 kilos. the wire broke.

§ 8. Fig. 3 shows the results of another experiment of the same kind, in which another piece of the same iron wire was stretched (after annealing), first by the application and removal of 35 kilos., then of 40, and finally broken, in the third loading, by a stress of 43 kilos. The thermoelectric currents were observed for every kilogramme of load, during application and removal. In the first loading (*a a*) while the wire was still soft the currents were irregular, but at 30 kilos., when the wire began to

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[*] *Cf.* a paper by Mr. G. W. VON TUNZELMANN on "The Production of Thermoelectric Currents in Wires subjected to Mechanical Strain," Phil. Mag., ser. 5, vol. 5 (1878), p. 339, where this result has been previously stated. In other respects the present writer's observations do not altogether agree with those of Mr. VON TUNZELMANN.

[†] *Loc. cit.*, § 109.

[‡] POGGEND. Annal., vol. 83 (1851), p. 469.

draw, they became steady, and the curves of E.M.F. and load were well defined throughout the remainder of the experiment, and have the same character as those already described. In this instance the whole diagram lies, to an unusual degree, on the positive side, probably because of some local peculiarity in the metal at the hot junction.

Here, again, the effect of each step in the process of drawing out is well marked (first at 30 kilos., then at 37 kilos., and last at 42 kilos.). At each extension the stretched portion becomes more and more positive. The want of coincidence between each "off" curve (or curve of E.M.F. and load during removal of load), and the succeeding "on" curve (or curve of E.M.F. and load during application of load), is as conspicuous as in fig. 2.

§ 9. This last is the most noteworthy of the phenomena now under review. In drawing attention to it in the paper submitted to the Royal Society in 1881, the writer was not aware that it had been previously noticed by any observer. He is now glad to be able to refer to an important paper by Herr EMIL COHN,* who has anticipated him in the discovery of this very interesting characteristic of the curves of stress and thermoelectric quality. In the figure which Herr COHN has given to illustrate his experiments with annealed iron wires, the process of loading has not been carried far enough to pass the negative maximum of E.M.F. shown in figs. 1, 2, and 3, and for this reason the curves have a comparatively simple form. But the "on" and "off" curves differ from one another in just the way which is shown by the independent evidence of the present writer's experiments.

§ 10. For the next group of experiments another piece of the same wire was taken, and, after annealing, was loaded with 21 kilos., which caused some permanent extension. This load was left on for a time, and was then removed. In all the subsequent loadings of this wire the load never exceeded 21 kilos., so that subsequent loadings caused no other than elastic strain.

The load of 21 kilos. was then repeatedly applied and removed. This brought the changes of E.M.F. to a cyclic state. They are shown in fig. 4, Plate 21, for the cycle of loads 0—21—0. Numerous experiments with other specimens have shown that the curves of fig. 4 are thoroughly characteristic of the behaviour of a piece of iron which, after annealing, has been stretched beyond its limit of elasticity, and is then alternately loaded and unloaded.

The great difference between the "on" and "off" curves will be realised when it is noticed that the negative maximum occurs at about 18 kilos. on the "on" curve, but at near 8 kilos. on the "off" curve, and that a load such as 4 kilos., when reached from a lower value, has associated with it a strongly *positive* quality on the part of the stressed piece, while if approached from a considerably higher value it is associated with an even more strongly *negative* quality.

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* "Ueber das thermo-electrische Verhalten gedehnter Drähte," WIED. Annal., vol. 6 (1879), p. 385. A few similar observations have more recently been published (three years after the present writer's first paper on the subject was read before the Royal Society) by R. OVERBECK, WIED. Annal., vol. 22 (1884), p. 344.

§ 11. One conspicuous feature in this difference of thermoelectric quality during loading and unloading is an apparent lagging of the thermoelectric change behind the change of stress. This aspect of the action may justify the use, for the sake of brevity in referring to it, of the name *hysteresis,* introduced by the writer in speaking of a similar phenomenon which presents itself whenever changes of magnetisation are caused by changes of magnetising force or by changes of stress.*

This hysteresis is (as Herr Cohn has already pointed out) an essentially *static* phenomenon. It is in no way affected by the speed at which load is applied and removed. In some of the writer's experiments the rate of loading and unloading was varied tenfold without causing any perceptible change in the form of the curves or in the area included between them. In other experiments a particular value of the load was kept for a long time constant, but the mere lapse of time appeared to be without effect. The value of the E.M.F. reached by any process of loading or unloading remains constant if the wire be undisturbed. The E.M.F. associated with any particular load is, of course, capable of assuming any value within a wide range, in dependence on the particular mode of loading by which the assigned load is reached. Any point within the area enclosed by the curves expresses a possible relation between E.M.F. and load, and the actual relation depends not only on the actual load, but on all the preceding states of load, especially on those which have immediately preceded the actual state. The effect of adding any load is by no means necessarily the same as the effect of removing that load, unless the operation be repeated, by itself, often enough to reduce the corresponding thermoelectric changes to a cyclic state.

§ 12. Figs. 5, 6, 7, 8, and 9, Plate 21, further illustrate the character of this hysteresis in the relation of thermoelectric quality to stress. They all represent experiments made on the wire of fig. 4. In fig. 5 the cycle 0—14—0 was performed, with the result that although the "on" branch had stopped short of the negative maximum (at 18 kilos. in fig. 4), nevertheless there was a very distinct negative maximum on the "off" branch. Fig. 5 is similar to the figure given by Cohn as representative of the behaviour of annealed iron. Other experiments showed the same thing to be true if the process of loading was stopped anywhere on the steeply-descending portion of the "on" curve. Fig. 6 shows the loop formed by superposing on the main cycle, 0—21—0, the small cycle, 11—3—11, starting at the point 11 kilos. on the main "on" curve. The dotted line in fig. 6 gives the result of a separate experiment, showing the effect of stopping unloading at 12 kilos. on the "off" curve and reapplying the full load. It illustrates how the points which define the relation of E.M.F. to load are not even limited to fall within the main "on" and "off" curves. Fig. 7 shows the curious changes of E.M.F. which occurred when at the point 16 kilos. on the "on" curve, the load was reduced to 7½, then reapplied, and the loading continued to 21 kilos. In the same way, fig. 8 shows the effect of loads 0—12—6—15. Fig. 9

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* Hysteresis, from ὑστερέω, *vide* Proc. Roy. Soc., vol. 33 (1881), p. 22; vol. 34 (1882), p. 39; vol. 36 (1883), p. 123; and Phil. Trans., vol. 176 (1885), p. 524.

shows the formation of a loop on the "off" curve at the point 4 kilos., by superposing the small cycle 4—10—4.

§ 13. The characteristic difference between the "on" and "off" curves is not, however, a mere lagging of changes of thermoelectric quality behind changes of stress, such as the lagging of magnetic change which is observed when the state of stress of a magnetised piece of iron is varied.* It is that, but it is something more. An inspection of the figures will make it evident that, in general, a reversal from loading to unloading, or from unloading to loading, causes at first a continuation of the same kind of thermoelectric change as has been going on before the reversal takes place. Thus on the "off" curve, towards the close of the removal of load, a rapid change of E.M.F. towards positive is going on, and when loading begins the change towards positive continues in the earliest part of the "on" curve. And it must be borne in mind that this happens irrespective of the speed of unloading and loading, and even if a long interval of time be allowed to elapse between the unloading and the next loading. Again (figs. 5 to 9), to stop loading at a point on the "on" curve, when a rapid change of E.M.F. towards negative is going on, and to begin unloading, causes the metal to continue at first to change towards negative. The only case in which the figures do not clearly bear out this remark is where, after the application of a load equal or nearly equal to the greatest value used in these experiments, the process of unloading begins. But careful experiments made with the express object of elucidating this point have given grounds for believing that, there as elsewhere, the very first effects of reversal of the process from loading to unloading were of the same sign as the effects of the process which was reversed. Certainly the phenomenon in question is much less well marked with high than with low values of the load, and is not (with high values) easily distinguished from inevitable errors of experiment. But it may be affirmed with confidence that generally, if not universally, the earliest effect of reversal from loading to unloading, or *vice versâ*, is to continue the same kind of thermoelectric change as has been going on just before the reversal takes place.

§ 14. *Effects of Vibration.*—These were studied by briskly tapping the wire during the application and removal of load, at the same time observing the thermoelectric currents. It was found that vibration destroys the effects of hysteresis nearly, though not quite, completely, and causes the "on" and "off" curves to approach towards coincidence. Fig. 10, Plate 21, illustrates this by showing the effect of applying to the same piece of wire as before the cycle of loads 4—19—4 without and with vibration. The wire was kept vibrating by tapping it briskly with a piece of wood, and the load was not reduced below 4 kilos., in order that the wire might remain tense enough for the tapping to take effect. Fig. 10A shows the changes of thermoelectric quality when the cycle 4—19—4 was gone through in the usual way without vibration, after several applications of the same cycle had brought about a cyclic state. Fig. 10B shows the effect of the same cycle, with vibration during the application and removal

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* Phil. Trans., vol. 176 (1885), p. 587, § 75. Proc. Roy. Soc., vol. 34 (1882), p. 43.

of the load. The influence of hysteresis is still observable, though to a far less degree than when the wire was undisturbed. The change caused by vibration will be best understood by considering the figs. 10A and 10B in their relation to the curves which have been already given for the complete cycle of loads, 0—21—0.

§ 15. In another experiment the influence of vibration in removing the accumulated effect of hysteresis was examined as follows:—The wire was loaded, without vibration, to 9 kilos. The galvanometer deflection, measuring the thermoelectric current, was then —99. Then, with the load of 9 kilos. kept constant, the wire was vigorously tapped, and the deflection changed to —144. Next the load was increased to 21 kilos. and then reduced to 9 kilos. The deflection was then —175. On tapping the wire, with the load of 9 kilos. kept constant, this changed to —150. Thus the total difference due to hysteresis of 175—99 or 76 scale-divisions was reduced by tapping to 6 divisions.

§ 16. In a supplement to his original communication to the Royal Society in 1881, the writer described a further experiment which showed that changes of magnetisation had an effect like that of vibration in removing the influence of hysteresis in the relation of thermoelectric quality to stress. When a constant load was applied, and the wire was gently stroked along its length by a bar magnet, the thermoelectric current changed in much the same way as it would have changed had the wire been subjected to a comparatively violent amount of mechanical disturbance, and to a degree much greater than could be explained as due to the slight mechanical disturbance caused by contact with the magnet. The influence of magnetisation, both in this and other respects, has formed the subject of many other experiments which will be described in the sequel.

§ 17. So far, only those results have been stated which were mentioned in the paper, "Part I.," communicated to the Royal Society in 1881. Figs. 1 to 10 inclusive have been copied from that paper. It remains to describe later experiments, made for the most part in 1883. Their principal object has been to examine the relation between the effects of stress on thermoelectric quality, on the one hand, and on magnetisation on the other. A glance at the figures given here and at those given elsewhere,* to illustrate the changes of magnetism produced by loading and unloading an iron wire, will show that there is a very striking likeness between them; enough likeness, in fact, to make the hypothesis very natural that stress acts on the thermoelectric quality of iron by altering its magnetisation, and that the variations of magnetism are the immediate cause of thermoelectric change. In the writer's earlier experiments no precautions were taken to rid the iron of magnetism to begin with, nor to place it in a position where it would escape magnetisation by the terrestrial field, and it was certainly in a more or less magnetic condition throughout the experiments. Sir W. THOMSON has shown† that change of magnetism does give rise

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* Phil. Trans., vol. 176 (1885), Plates 62, 63; Proc. Roy. Soc., vol. 34 (1882) pp. 43, 44.

† *Ibid.*, vol. 146 (1856), p. 722, § 134.

to change of thermoelectric quality, and it is well known from the work of THOMSON and others that stress affects the magnetism of iron, whether that be residual or induced. Herr COHN has not overlooked the possibility that the thermoelectric effects of loading may be explained as secondary results of the changes of magnetisation which it causes, but says that, while he has no conclusive evidence either way, he inclines to the view that the observed phenomena are not to be explained as results of changes in magnetism.

The matter is one of much interest, for if the results are due to stress simply, and not to the magnetic changes caused by stress, we have here a novel instance of hysteresis, entirely distinct from the instances which are common in magnetic phenomena.

§ 18. To put the question to a conclusive test the writer, in his second series of experiments, employed independent means to produce and to measure magnetisation in the loaded wire. In some experiments the wire was magnetised to begin with, or was exposed throughout to a constant magnetising force, while the effects of loading and unloading on the thermoelectric quality were examined. In others the wire was completely demagnetised before loading began, and was kept free from magnetising force during the process. In others still the effects of magnetisation alone on thermoelectric quality were measured, by varying the magnetic field while the wire was either without load, or was kept loaded with a constant weight.

The results proved beyond question that the effects of stress on thermoelectric quality (though modified by the presence of magnetisation) are not secondary effects of the changes of magnetisation; and that the hysteresis of thermoelectric quality with regard to stress is a thing distinct from the hysteresis of magnetism, though probably proceeding from the same peculiarity in the molecular mechanism.

§ 19. In these experiments the loading was done by lead weights, instead of by a water-tank. The wire was held in much the same way as before, with the hot junction in a vessel of heated oil, and the cold junction simply exposed to the air. The wire was set in a sloping position at right angles to the lines of terrestrial magnetic force; and over it, covering the whole of the portion under stress, was slipped a tube, on which a magnetising solenoid was wound. Over against the upper end of the stressed portion was a mirror magnetometer, to measure the magnetisation of the part under stress. The continuations of the iron wire on either side of the part under stress were led away so that they scarcely affected the magnetometer, and were as much as possible prevented from becoming magnetised.

§ 20. An arrangement was provided by which the wire would be demagnetised by reversals, in the manner described in the writer's paper of "Researches in Magnetism,"* by passing a continuously and gradually diminishing current through the solenoid, while the direction of the current was rapidly reversed many times.

The magnetisation of the wire, and the magnetising force applied to it, were

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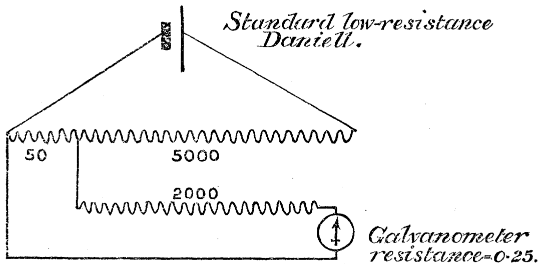
* Phil. Trans., vol. 176 (1885), p. 539, § 19.

determined in absolute measure by the same methods as those described in the paper referred to. To reduce the thermoelectric effects to absolute measure, the resistance of the circuit, consisting of the iron wire, leading wires, and galvanometer, was carefully determined, and the "galvanometer constant" was found by passing through it the current produced by exposing the ends of a coil of large and known resistance to a difference of potential amounting to rather less than $\frac{1}{100}$, $(\frac{2}{207})$ of the E.M.F. of a standard Daniell's cell, the fractional potential being furnished in the manner sketched in fig. 11. From this was calculated the deflection which, in the actual thermoelectric circuit, would be produced by 1 microvolt (1 volt × 10^{-6}), and the thermoelectric effects are expressed in microvolts.

Fig. 11.



§ 21. In all the following experiments pieces of iron wire from the same bundle were used, and the experiments of fig. 12 to fig. 31 inclusive were made with the same specimen. The wire was 0·64 mm. in diameter originally. After annealing it was stretched with a load of 12 kilos., which gave it a considerable permanent set, and reduced its diameter to 0·61 mm. The subsequent loadings were kept within this amount, and consequently caused no further permanent set.

§ 22. In the first experiment, fig. 12, the wire had some residual magnetism, though no magnetising field was in action, in the direction of its length. The cycle of loads 0 — 11 kilos. — 0 was repeated several times, and the thermoelectric and magnetic effects were observed. In this case they have not been reduced to absolute measure; and the scale readings are stated below as they were taken. The magnetometer and galvanometer readings are taken from the true zero.

Load.	Magnetometer.	Galvanometer (thermoelectric current).	Load.	Magnetometer.	Galvanometer (thermoelectric current).
kilos.			kilos.		
0	37	50	11	77	−12
2	45	69	10	78	−23
4	70	12	8	80	−50
6	84	−26	6	84	−85
8	84	−46	4	86	−79
10	79	−24	2	68	−23
11	77	−12	1	56	+18
			0	41	50

Fig. 12, Plate 21, shows the changes of thermoelectric current in relation to load in this experiment, and fig. 12A the (simultaneous) changes of magnetism, also in relation to load. The latter are not so perfectly cyclic as are the former, and in other respects, which will be evident on a close inspection, the two curves present noticeable features of difference, as well as a very striking general similarity.

§ 23. The effect of magnetisation, separately, was then examined. While the wire was kept free from load a current was established in the magnetising solenoid, and strengthened step by step until the magnetisation was as great as the maximum value reached by loading in the previous experiment. This was found to produce very little change of thermoelectric quality—only about one-twentieth as much as occurred during loading. It was clear from this that the thermoelectric effect of stress was not a secondary result of the change of magnetisation.

The same result was confirmed by other experiments, in which the wire was demagnetised as completely as possible by the method of reversals before the process of loading began. In such a case it was found that the thermoelectric effects of load were as marked as ever, although the wire was, and remained, sensibly free from magnetisation during loading and unloading.

§ 24. To examine more particularly the influence of magnetism on the thermoelectric effects of stress, the same wire was used in a group of experiments, whose results are exhibited in figs. 13 to 18, Plate 22. In the experiments in this group the wire received more or less magnetisation to begin with, by the application of a magnetic field which was maintained constant during the process of loading and unloading. The changes of magnetism and the changes of thermoelectric quality, produced by loading and unloading, were then observed, and both are shown graphically in their relation to the loads, and in absolute measure. The temperatures of the junctions were 160° C. and 20° C.

In each case, after the magnetising field had been brought to a constant value, the load was raised from 0 to 12 kilos. (which was the stress originally employed in stretching the specimen, § 21). It was then reduced to 0, then reapplied up to 12 kilos., and finally reduced to 0. The effects of the first application and removal are shown in each figure by full lines, and the effects of each second application and removal by dotted lines.

First, the wire after being set in position at right angles to the earth's lines of magnetic force was demagnetised by the method of reversals, and then loaded, while readings of the thermoelectric effect were taken. These are given, reduced to microvolts, in Curve Ia, fig. 14. The magnetometer was watched during this process, but it remained undeflected, there being neither residual magnetism nor inducing field. The second "off" curve in Ia was so nearly coincident with the first "off" curve that it has not been drawn.

§ 25. Next (the wire being free from load) a current was established in the magnetising solenoid, of such strength as to give an intensity of magnetisation $\mathfrak{I}=160$

c.g.s. units. Then, while the current was kept up, the process of loading and unloading was gone through twice. The resulting changes of magnetism are shown in fig. 13, Curve II, and the simultaneous changes of thermoelectric quality in Curve II*a*, fig. 15. In order to make the curves of magnetism and thermoelectric quality have a similar aspect, the former are drawn as they would appear if the sign of magnetisation (which is arbitrary) were reckoned negative.

§ 26. Next, the magnetisation was raised to $\mathfrak{I}=228$ by raising the field to a higher value, which was maintained while loads were applied and removed twice. The magnetic results are shown in Curve III, fig. 13, and the thermoelectric results in Curve III*a*, fig. 16.

§ 27. Next, in the same way, the magnetisation was raised to $\mathfrak{I}=598$, and the same procedure followed. The corresponding curves are IV, fig. 13, and IV*a*, fig. 17.

§ 28. Finally $\mathfrak{I}$ was further raised to 696, and the wire loaded. The magnetic and thermoelectric curves for this last case are V, fig. 13, and V*a*, fig. 18, respectively.

§ 29. The magnetic Curves II, III, IV, and V are similar to others published by the writer in a former paper,* and their characteristics need not be dwelt on here. A comparison of the thermoelectric curves with them and with each other shows well the gradual transformation which these undergo in consequence of increased magnetism, and the curious likeness which subsists between the effects of hysteresis in the two cases. In both, the effects of the second loading and unloading differ from the effects of the first in much the same manner, except that there is little in the thermoelectric curves to correspond to the immense changes of magnetism which take place when loading begins. In both, the ascending limb of the "on" curve (corresponding to comparatively high values of load) is a small feature when the magnetisation is weak, and becomes transformed into the principal feature as the magnetisation becomes intense. It is exceedingly interesting to trace the change from the familiar form shown of I*a* to that of V*a*, whose connexion with the other would scarcely be suspected were the intermediate links absent. This transformation, although occurring to some extent in both sets of curves, is much more complete in the thermoelectric than in the magnetic group. One of its results is that, whereas in ordinary conditions the general effect of stress on thermoelectric quality is that a moderate pull makes the wire more negative, this effect is reversed when the wire is strongly magnetised. Another general effect of strong magnetisation is that it reduces the influence of hysteresis, making the "on" and "off" curves less widely asunder than they otherwise are. Another is that it makes the wire, when there is no load, thermo-electrically negative. The positive maximum which occurs at an early stage in the first loading is very conspicuous in I*a*, less so in II*a*, and absent in the remaining figures. The similar positive maximum which occurs during the second loading is present in I*a*, II*a*, and III*a*, but has become a mere inflection of the curve in IV*a* and V*a*. The

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* Phil. Trans., vol. 176 (1885), p. 523.

negative maximum on the "off" curve occurs later and later during the removal of load as the intensity of magnetisation increases.

§ 30. Figs. 19–22, Plate 23, exhibit the results of another experiment, on the same wire, made with the object of comparing the changes of magnetisation and thermoelectric quality caused by changes of magnetising force with those caused by changes of load.

The wire—free from load—having been demagnetised by reversals, was carried through a cycle of magnetisation by gradually applying a magnetising force $\mathfrak{H}$ of nearly 17 c.g.s. units, gradually withdrawing and reversing, and finally re-reversing $\mathfrak{H}$, while the magnetisation and thermoelectric quality were measured in the usual way. The consequent changes of $\mathfrak{I}$ in their relation to $\mathfrak{H}$ are shown in fig. 19. The simultaneous changes of the thermoelectric E.M.F. are shown, in their relation to $\mathfrak{I}$, in fig. 20. The precise form of the curves in fig. 20 is somewhat uncertain, in consequence of irregularities which were perhaps due to the difficulty of keeping the thermal condition absolutely constant during so long an experiment. The effect of the first magnetisation is shown by the full line (in fig. 20), of the first reversal by the lower broken line, and of the second reversal by the upper broken line. There is not much evidence of hysteresis in the relation of thermoelectric quality to intensity of magnetisation.

Then the wire was demagnetised by reversals, the magnetising field was reduced to zero, and the process of loading and unloading (up to 12 kilos.) was performed. Fig. 21 shows the resulting thermoelectric changes to the same scale of E.M.F. as is used in fig. 20. During the process the magnetometer was observed, and a very slight residue of magnetism which had escaped the demagnetising process was seen to go through the minute changes shown in fig. 21, where $\mathfrak{I}$ is drawn to the same scale as in figs. 19 and 20. It is obvious, by comparison of figs. 20, 21, and 22, that these changes of $\mathfrak{I}$ were wholly incompetent to account for the changes of E.M.F. in fig. 21. The changes of E.M.F., caused even by the strongest magnetisation reached in the experiment, fell short of those which occurred during the application and removal of load when the wire was almost wholly free from magnetism.

§ 31. The effect of magnetisation on the thermoelectric quality of iron is that longitudinal magnetisation, in either direction, makes the magnetised part more negative in the conditions examined in fig. 20. In that case there was no load on the wire, and the question suggested itself: How is this effect of magnetisation modified by the presence of a constant stress? To answer this question a group of experiments was carried out, whose results are exhibited in figs. 23, 24, 25, and 26, Plate 23. In each of these the wire, demagnetised by reversals to begin with, was alternately magnetised first in one and then in the other direction, as in figs. 19 and 20. The relation of the thermoelectric E.M.F. to the intensity of magnetisation $\mathfrak{I}$ is shown by the figures. Fig. 23 is for the case of no load, and is virtually a repetition of the previous experiment of fig. 20. Fig. 24 is for the case where a constant load of 3 kilos. was applied to the wire. Fig. 25 is for a constant load of 6 kilos., and fig. 26 for 12 kilos. (Figs. 23, 24, and 25 are drawn about the same axes; fig. 26 is drawn about a separate axis of $\mathfrak{I}$

to avoid confusion.) After each of these loads was applied, the wire was subjected to the process of demagnetising by reversals before the magnetisation, whose effects were to be noted, was begun. The importance of this will appear in the sequel. (§§ 32–34.) In all four figures the greatest magnetising force applied was nearly the same, but the magnetisation in figs. 24 and 25 (and to a less degree in fig. 26) was greater than in fig. 23 on account of the fact that the presence of a moderate amount of load increases the magnetic susceptibility of iron, especially of iron which is treated as the specimen under test was treated.*

The figures show that the presence of load diminishes the general thermoelectric effect of magnetisation, and finally reverses it when the load is great. For the reason already given, the form of these curves is not very precisely defined, and the evidence of hysteresis in the relation of E.M.F. to magnetism is, at the best, inconclusive.

§ 32. It has been said that in figs. 24, 25, and 26, after the load was applied, the wire (although then not at all magnetic) was subjected to the process of demagnetising by reversals before the observations were taken. This was because it was found that the process in question was very effective in wiping out what may be called the historical traces of previous actions that are left in consequence of hysteresis. This is a very interesting part of the subject, which may easily be explained by a few examples. Thus, if in the experiment of fig. 24 the wire had simply been demagnetised by reversals with no load, and then loaded to 3 kilos., before the observations were begun, the results would have been (during the first application of magnetising force) very different from those actually obtained. The difference of conditions would have been that, owing to the accumulated effects of hysteresis during the application of load from 0 to 3 kilos., the wire would have possessed a distinctly altered molecular structure from that which it possessed when (as in the actual conditions of the experiment) this accumulated result of hysteresis was removed by repeating the process of demagnetising by reversals after the load was on. Precisely analogous phenomena have been noticed in the writer's paper on magnetism,† where it has been shown that the magnetic susceptibility of iron depends not only on the load present, but on past values of the load, until by the process of demagnetising by reversals the metal is made indifferent to *how* the actual state of load has been reached.

§ 33. In fig. 27, Plate 23, the wire, previously loaded to 12 kilos. and unloaded many times, was subjected to the process of demagnetising by reversals, while the load was off. The thermoelectric E.M.F. was then +6·2 microvolts (see *a*, fig. 27). Then load was applied, up to 12 kilos. (Curve *ab*) and removed (Curve *bc*). The want of coincidence between *c* and *a* represents a difference of molecular structure, caused by the application and removal of load. If the process of demagnetising by reversals had then been repeated, the E.M.F. would have risen to the value shown by *a*. It must be understood that throughout the loading and unloading there was no magnetic field in action and no magnetism in the wire. Next, loading was resumed (Curve *cd*) and continued up to 3 kilos. That load was then kept constant, while magnetisation of the wire

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* Phil. Trans., vol. 176 (1885), p. 609, § 93.

† *Ibid.*, p. 612, §§ 96–101.

was begun. The results of magnetising are shown in the upper part of fig. 28, Plate 23, which is a curve of E.M.F. and $\mathfrak{I}$. Starting from *d* (fig. 28)—a state identical with *d* in fig. 27—the wire was magnetised until with a value of $\mathfrak{I}=780$ the point *e* was reached. Then gradual reversal of the magnetisation carried the E.M.F. through the values shown by the dotted line *ef.*

§ 34. Next, the wire was demagnetised by reversals and the whole process of loading and unloading repeated twice, but at the second time the unloading was stopped while 3 kilos. remained on the wire. The E.M.F. was then found to be $-2{\cdot}3$ microvolts—a state shown by the point *g* in fig. 28. Then, with the load constant, magnetisation gave the Curve *gh,* and reversal of magnetisation gave the Curve *hi.*

Both parts of fig. 28, therefore, represent the thermoelectric effects of magnetising, while a constant stress of 3 kilos. is maintained. But they differ in this, that in the upper part of the figure that load was reached by increment from 0 to 3 kilos., whereas in the lower part of the figure the load was reached by decrement from 12 kilos. This difference in the history of the loads causes a difference of molecular structure which is nearly, though perhaps not altogether,* obliterated by a single application of a strong magnetising force, and in its obliteration gives rise to the widely different curves *de* and *gh,* both of which represent the first effect of magnetisation on the thermoelectric quality of the same piece of iron in one and the same constant state of stress.

Fig. 28 will make it clear why in the series of experiments shown in figs. 23–26 the process of demagnetising by reversals was performed *after* each of the several loads was applied.

§ 35. The experiment was then extended, in the same manner as before, to determine the thermoelectric effects of magnetising under 6 kilos. of load, starting in one case from the point 6 kilos. on the "on" curve (reached, after demagnetisation, by the loads 0—12—0—6), and in the other case from 6 kilos. on the "off" curve (reached, after demagnetisation, by the loads 0—12—0—12—6). The results are shown in fig. 29, Plate 23, from which it will be seen that the first magnetisation gives widely different curves of E.M.F. and $\mathfrak{I}$ in these two cases, but the subsequent reversal of magnetisation gives effects so nearly similar in the two cases that they have been drawn by a single line (the dotted line of fig. 29).

§ 36. Finally, fig. 30, Plate 23, shows in the same way the effect of a first magnetisation and subsequent reversal of magnetism, under a constant load of 12 kilos., reached, after demagnetisation, by loading to 12, unloading to 0, and loading again to 12 kilos.

§ 37. The experiments of figs. 28, 29, and 30 differ from those of figs. 23–26 in this respect, that in the latter the effects of hysteresis, accumulated during the process of loading or unloading which preceded magnetisation, were wiped out by the process of

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* The Curves *ef* and *hi* differ by an amount which may possibly be due to variation of thermal conditions in this protracted experiment.

"demagnetising by reversals" before the magnetisation, whose effects were to be observed, was begun; whereas in figs. 28–30 the molecular instability to which hysteresis in loading has given rise is being overcome by the first magnetisation, and this is causing changes of thermoelectric quality which are superposed on what may be called the normal variation due to magnetism. In the experiments of figs. 23–26 the process of "demagnetising by reversals" was resorted to, after each load was on the wire, not for the purpose of removing magnetism (since there was none to remove), but in order to produce a molecular commotion by which this state of instability should be destroyed, and the reminiscence of previous stresses be dissipated.

§ 38. To illustrate more fully the effect of the process of "demagnetising by reversals," an experiment was made whose results are set forth in fig. 31, Plate 23. After loading in the usual manner (the wire being free from all residual magnetism, and exposed to no magnetic field), up to 2 kilos. (Curve *ab*, fig. 31), the process of demagnetising by reversals was gone through while the load was kept constant. The E.M.F. fell in the process from 11·2 to 5·35 microvolts (*bc*, fig. 31). Then loading was continued, up to 4 kilos., giving the Curve *cd;* and at 4 kilos. the process of reversals was again performed, causing a fall of E.M.F. from 5·75 to −0·5 microvolt. Further loading (up to 6 kilos.) gave the Curve *ef*, and the process of reversals gave the fall *fg:* further loading gave the Curve *gh*, and so on, the process of reversals being applied at 8, 10, and 12 kilos. Similarly, at each step of 2 kilos. on the "off" curve, the process of reversals was applied with results which (along with those of the intermediate unloadings) are shown in the figure by dotted lines. As the figure is somewhat involved, the observed deflections and the values of E.M.F. calculated from them are given numerically below :—

Load.	Galvanometer deflection.	E.M.F.	Load.	Galvanometer deflection.	E.M.F.
kilos.		microvolts.	kilos.		microvolts.
0 (after reversals)	165	9·7	11	4	+0·25
1	191	11·2	10	− 18	−1·05
2	191	11·2	After reversals	− 27	−1·25
After reversals	91	5·35	9	− 55	−3·25
3	109	6·4	8	− 80	−4·7
4	98	5·75	After reversals	− 70	−4·1
After reversals	− 8	−0·5	7	− 83	−4·85
5	+15	+0·9	6	− 90	−5·3
6	+11	+0·65	After reversals	− 56	−3·3
After reversals	−50	−2·95	5	− 78	−4·6
7	−28	−1·65	4	− 75	−4·4
8	−32	−1·9	After reversals	− 22	−1·3
After reversals	−80	−4·7	3	− 17	−1·0
9	−47	−2·8	2	+ 7	+0·4
10	−20	−1·15	After reversals	+ 70	+4·1
After reversals	−34	−2·0	1	+ 61	+3·6
11	− 2	−0·1	0	+ 93	+5·45
12	+34	+2·0	After reversals	+143	+8·4
After reversals	+21	+1·25			

Temperatures, 144° C. and 17° C.

From these results, which have been confirmed by other independent experiments, it will be seen that the process of "demagnetising by reversals" has an effect closely similar to that of mechanical vibration in removing traces of hysteresis. (*Cf.* §§ 14, 15.)

§ 39. One very remarkable feature in fig. 31 is the positive maximum (or negative minimum) which the wire passes through when, after the process of reversals, one continues to add more load. This maximum occurs for all values of the load less than 8 kilos., and is found, generally, when rather more than 1 kilo. has been added to the load present during the process of reversals. Further, during the removal of load a negative maximum (or positive minimum) occurs in each stage, as is shown by the dotted curves. These features are conspicuous in the descending limb of the main curve, that is to say, in that part of the diagram which lies between the zero of load and a load of about 8 kilos. In the right-hand portion, or ascending limb, the effects of hysteresis are comparatively indistinct, and the process of reversals affects the actual and subsequent values of the E.M.F. to a much less degree.

§ 40. Experiments like that of fig. 31 were made, with this difference, that instead of applying the process of "demagnetising by reversals" at the points *b*, *d*, *f*, *h*, and so on, the wire was briskly tapped, so that a merely mechanical in place of a magnetic disturbance was set up. Then, when the vibration had subsided, and the altered value of the E.M.F. had been observed, the process of loading was continued. The results were entirely similar to those of fig. 31. After tapping (under any load up to 6 or 8 kilos.) the resumption of loading caused the E.M.F. to have a positive maximum or negative minimum, and the resumption of unloading gave a positive minimum or negative maximum, as in that figure. The molecular state produced by brisk mechanical vibration is like that produced by applying the process of reversals, at least in these particulars—that the traces of previous stress-changes are more or less completely obliterated, and the next succeeding application or removal of stress causes similar complex variations in thermoelectric quality.

§ 41. Attention has already (§ 13) been drawn to the fact that the characteristic difference between "on" and "off" curves of load and thermoelectric quality is not a mere lagging in the change of thermoelectric quality. If it were, a reversal, say, from unloading to loading would cause in the earliest stages no thermoelectric effect, instead of causing (as it generally does) an effect whose sign is the same as that which was previously occurring during the unloading. It occurred to the writer to inquire whether this might not be accounted for as follows, by the instability of molecular structure which, generally speaking, exists at any point in the process of loading or unloading. To fix the ideas, suppose that, after a considerable load has been on, the process of unloading is stopped at a point at or near the zero of load. Before the stoppage the E.M.F. has been rapidly becoming more positive. But the metal is, owing to hysteresis, in a less positive state than it would reach if we were now to vibrate the wire, or subject it to the process of "demagnetising by reversals." In the circumstances assumed any disturbance will produce a change towards positive.

But suppose that no disturbance takes place, and let the process of loading be begun. The observed effect is, first, a change towards positive, then soon a positive maximum, and then a great and continued change towards negative. It is open to conjecture that the first (positive) effect of loading is due to the mere molecular disturbance associated with change of stress; that though the proper effect of loading is negative, that effect lags, and superposed on it there is a positive effect due to the simple disturbance caused by loading, acting on the unstable molecular structure to which the previous unloading has given rise. This view, were it tenable, would certainly make the fact less extraordinary than it otherwise is, that in general a change from loading to unloading, or *vice versâ*, continues the same kind of thermoelectric change as has been going on before.

But this view appears to be negatived by the experiment of fig. 31, and by similar experiments made with mechanical shaking substituted for magnetic shaking. For we find that at *a*, for instance, in spite of the violent molecular commotion which preceded the loading, nevertheless the first effect of loading is to carry the wire through a positive maximum of thermoelectric quality, before beginning that change towards negative which is the main consequence of any moderately great load. And after every other shaking up at intermediate points in the loading the same curious positive maximum comes in before the main trend of the "on" curve is resumed. It is clear that this puzzling characteristic of the curves cannot be ascribed to any ordinary mechanical agitation which may be assumed to accompany changes of stress; for not only does it appear after the metal has been thoroughly shaken into what may be presumed to be a stable state, but at points, such as *c*, *e*, *g*, &c. (fig. 31), it asserts itself in the direction *opposite* to that in which the thermoelectric quality has been altered by mechanical or magnetic disturbance. And it is not a little remarkable that the phenomenon under discussion has no counterpart in the (otherwise similar) hysteresis which the induced or residual magnetism of a piece of iron exhibits when it is forced to vary by application and variation of stress.

§ 42. Up to this point all the experiments of the new series (from § 21 onwards) were made with the same sample of iron wire, which, as has been stated (§ 21), was a piece that had, after annealing, been moderately stretched beyond its elastic limit. Other experiments with other samples, treated in the same way, confirmed the results which have been described. The examples which have been cited are chosen out of a much larger number of tests, which need not be particularly described, as they exhibited no features which have not been already referred to. In the experiments which have been given (§§ 21 to 38) the hot junction had a temperature of from 130° C. to 160° C., and the cold junction a temperature of from 15° C. to 20° C. Care was taken to preserve the temperatures nearly constant during any one experiment, but it was not considered necessary to give them strictly the same values from day to day, as the aim of the research was to study, not the dependence of thermoelectric effects on temperature and temperature differences, but those peculiar features in the thermoelectric behaviour of iron, with any assigned junction temperatures, which have now been fully exhibited by means of curves.

§ 43. Experiments were made with other pieces cut from the same bundle of iron wire (diameter = 0·64 mm.), but not annealed, to test the changes of thermoelectric quality which are caused by longitudinal pull in iron in the hard-drawn state. The results of two representative experiments of this kind with two distinct pieces of wire are shown in figs. 32 and 33, Plate 23. In both cases the portion of the wire between the hot and cold "junctions" was, for some accidental reason, rather strongly negative with respect to the adjoining portions when there was no load, but became positive while under a strong pull.

In the experiment of fig. 32, the temperatures were 135° C. and 21° C. The wire was loaded with 13 kilos., then unloaded, and during the next loading the observations shown in fig. 32 were taken. The form of the curve is similar to that given by COHN for hard wire, except that the loop which hysteresis causes at the upper end appears to have escaped his notice. The general result is that loading has a *positive* effect; and, further, that a mechanically hard wire behaves very similarly to a strongly magnetised but much softer wire. That it is so will be seen by comparing fig. 32, where the wire is hard-drawn but not magnetised, with figs. 17 and 18, Plate 22, where the wire was only slightly hardened by stretching, but was strongly magnetised. Obviously we should expect that iron in a state of hardness intermediate between these would give results resembling those of figs. 15 and 16, which refer to moderately magnetised wires; and this corollary has been verified by experiment with a piece of the same iron which was annealed, but much less perfectly than in the former experiments, and was then loaded and unloaded without magnetisation. In fact the series of figures 14 to 18, which exhibit the effects of various degrees of magnetisation, serve also to illustrate how under various degrees of mechanical hardness there is continuity in form between the familiar type of fig. 4, or 12, or 14, or 21, and the very different looking curve of fig. 32. The phrase, "mechanical hardness," must be understood here to refer only to the kind of hardness which comes of permanent strain, such as stretching or wire-drawing; for the writer has made no experiments to determine whether a like relation holds between the various degrees of hardness which can be given to steel by variations of temper apart altogether from strains. Hardness of the latter kind may confidently be expected to reduce hysteresis, which has now been shown to be reduced by the presence of load, by the existence of a magnetic condition, and by the existence of a state of non-elastic strain or "set."

§ 44. In fig. 33 the temperatures were 143½° C. and 19° C. The wire—an unannealed specimen—had a load of 14 kilos. applied to it; this was removed and a load of 12 kilos. was applied and removed while the observations were taken whose results are exhibited in the figure. This figure, along with the last, shows that the curves for hard-drawn iron differ from the curves for softer wire chiefly in this, that the negative maximum, familiar in the earlier figures, is now shifted so close to the line of zero load as to appear as a mere inflection in the "on" curve, though still present in the "off" curve; while, as part of the same action, the outer or ascending limb of the curve becomes the conspicuous portion and occupies nearly the whole figure.

§ 45. At the conclusion of the above experiments with iron, the effects of stress on the thermoelectric quality of certain other metals were examined in the same way, with the view of testing for hysteresis in changes of thermoelectric quality caused by applying and removing longitudinal pull. Wires of silver, copper, lead, magnesium, and german silver were tried, but in no case did the results of loading and unloading afford any evidence of hysteresis. In curves showing the relation of thermoelectric E.M.F. to load, the "on" and "off" curves did not differ by more than the limits of experimental error. With all the wires named, loading produced in the part loaded a change towards *positive*,* and the change remained nearly proportional to the stress up to the largest value to which the load was increased. In silver and magnesium the E.M.F. rose to about 4 microvolts when the load was increased to as large a value as it was judged safe to apply without risk of breaking the wire; in the other metals the range of thermoelectric change was much smaller.

Another metal examined was aluminium, which, unlike the others, changed to *negative* when loaded. The change was very small, amounting to only half a microvolt under the greatest load. A tin wire showed no measurable change of thermoelectric quality, either positive or negative, when loaded up to its breaking point.

So far there is no evidence that the peculiar behaviour of iron, the study of which has been the object of this paper, is not peculiar to that metal. It will be interesting to see whether similar characteristics are exhibited by the other strongly paramagnetic metals, nickel and cobalt.

§ 46. The changes of thermoelectric quality through which a piece of iron passes when subjected to varying amounts of stress are so complex that it seems impracticable, until our knowledge of molecular structure is greatly extended, to attempt any mechanical hypothesis by way of explanation. With respect to one very curious feature, however, to which attention has been drawn in §§ 13, and 39–41, it may be worth while to point out an analogy which suggests a connexion between the structure of iron and that of a granular medium. Professor OSBORNE REYNOLDS has pointed out† that when a substance composed of granules in contact is subjected to

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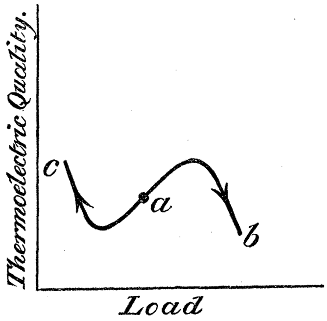
* *Cf.* THOMSON, Phil. Trans., vol. 146 (1856), p. 729, § 144.

† Phil. Mag., ser. 5, vol. 20 (1885), p. 469, "On the Dilatancy of Media composed of Rigid Particles in Contact."

strain, distortion is accompanied by certain complex changes of density, which depend on the arrangement of the particles. Thus, if a bag of shot or sand be shaken into the stable arrangement which corresponds to maximum density, and then be subjected to stress by (say) compression between two planes, the density will at first diminish, and then, as the stress is increased, will pass a minimum and begin to increase. So the thermoelectric quality of a piece of iron which has been shaken into a condition of molecular stability changes, first, towards (say) positive and, later, towards negative (fig. 31), when stress is applied and increased. Here, however, we are dealing with a quality, which, unlike density, is directional; and the changes have, in fact, the reverse signs from those just stated if the direction of the applied stress is reversed. Thus, let *a* (fig. 34) be a point expressing the relation of thermoelectric E.M.F. to load, which is reached by tapping the metal or by exposing it to the process of demagnetising by reversals. If from this point we go on loading we have the curve *a b*. If from the same point we had begun to unload we should have had the curve *a c*.

Fig. 34.



The property of dilatancy, which Professor Reynolds has shown that granular media possess, does not in itself afford any clue to the changes which a directed quality like that now under examination suffers when the condition of stress is varied. But the same considerations (which explain why, in the changes of volume accompanying strain in a granular medium after vibration, there is a point of inflection similar to that which is the most striking feature of these thermoelectric curves) suggest that a granular medium may be the kind of molecular mechanism required to account for the characteristics which have been described in this paper, and that the remarkable feature in the hysteresis of thermoelectric quality with regard to stress commented on in §§ 13 and 41 is to be attributed to a periodic arrangement of granules. The difficulty of any dynamical explanation is not a little increased by the fact that the variations of magnetism which accompany variations of stress, while otherwise not very dissimilar to the variations of thermoelectric quality, exhibit none of this inflection, either when a change takes place from loading to unloading (or from unloading to loading), or when the process of loading or unloading is resumed after the metal has been subjected to vibrations while supporting a load of any assigned value.

[September 17, 1886. The influence of magnetisation on the thermoelectric quality of iron forms the subject of a chapter in Messrs. BARUS and STROUHAL'S comprehensive memoir "On the Physical Characteristics of the Iron Carburets."* Their experiments, like those of the writer, confirm THOMSON'S observation that longitudinal magnetisation makes iron thermoelectrically negative (in the sense used in this paper). Their absolute measurements of the effect are of the same order of magnitude as those in the examples cited above. Messrs. BARUS and STROUHAL have investigated with much fulness the thermoelectric effects of tempering, in the case of steel, and have pointed out that these are far greater than the effects of magnetisation. It may be added that they are also far greater than the effects which result from hardening by mechanical strain. Iron hardened by stretching is thermoelectrically positive to soft iron : glass-hardened steel is also thermoelectrically positive to soft steel, but to a much greater degree.—J. A. E.]

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* Bulletin of the U. S. Geological Survey, No. 14, 1885.

Ewing.

Fig. 1. (§6.)

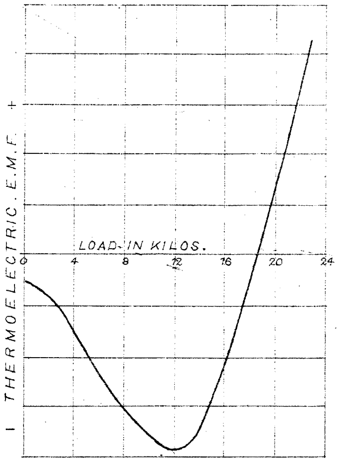
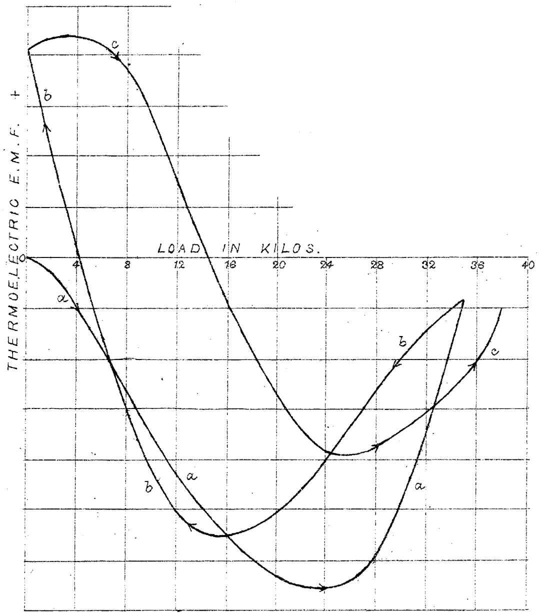


Fig. 2. (§7.)



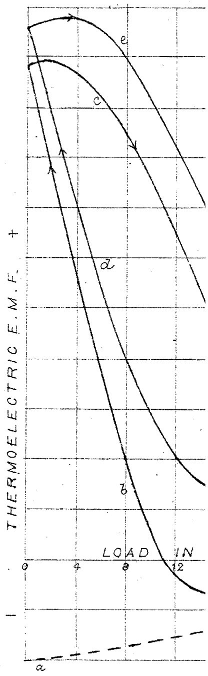


Fig. 4. (§10.)

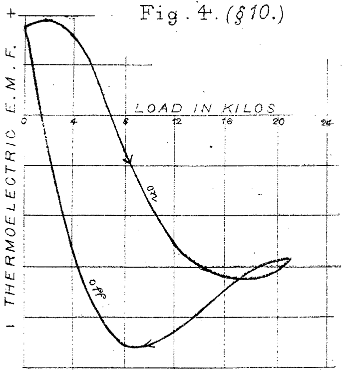
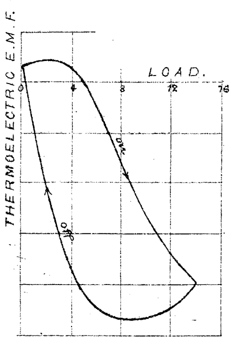


Fig. 5. (§12.)



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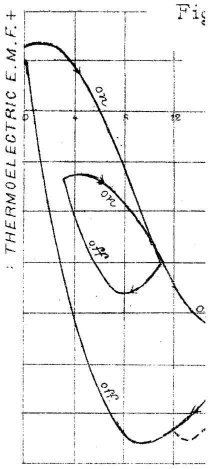


Fig. 7. (§12.)

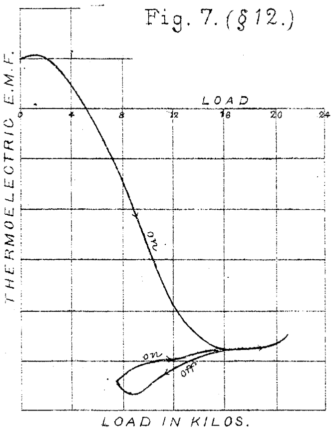


Fig. 8. (§12.)

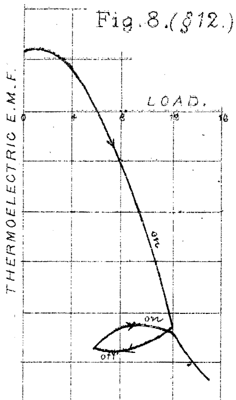


Fig.

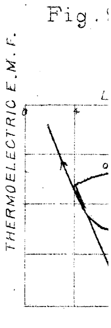


Fig. 3. (§ 8.)

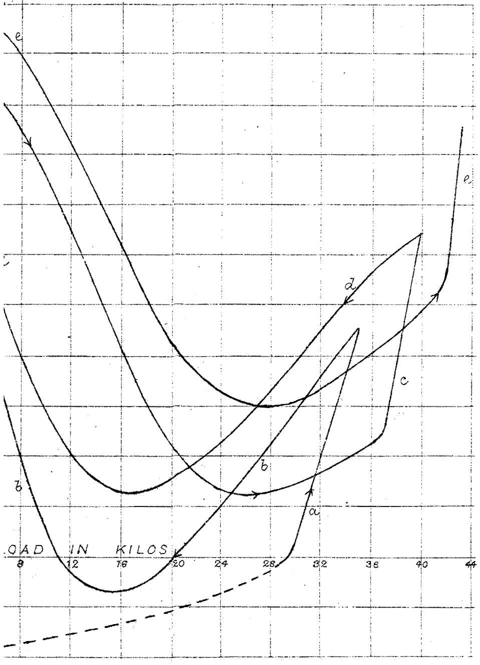


Fig. 6. (§ 12.)

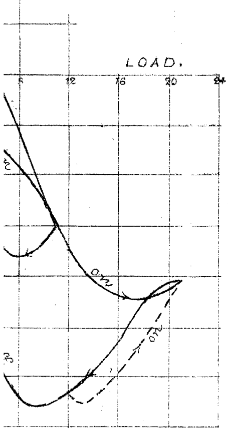


Fig. 9. (§ 12.)

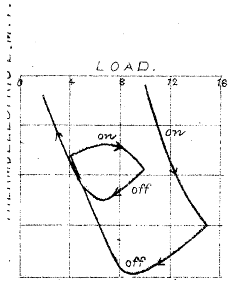
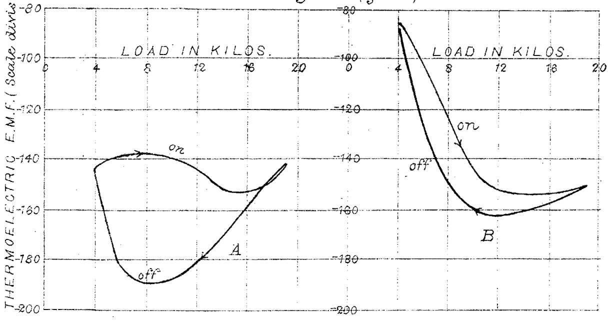


Fig. 10 (§ 14.)



Effects of vibration

A without vibration.
B with vibration.

Same wire; same cycle of loads.

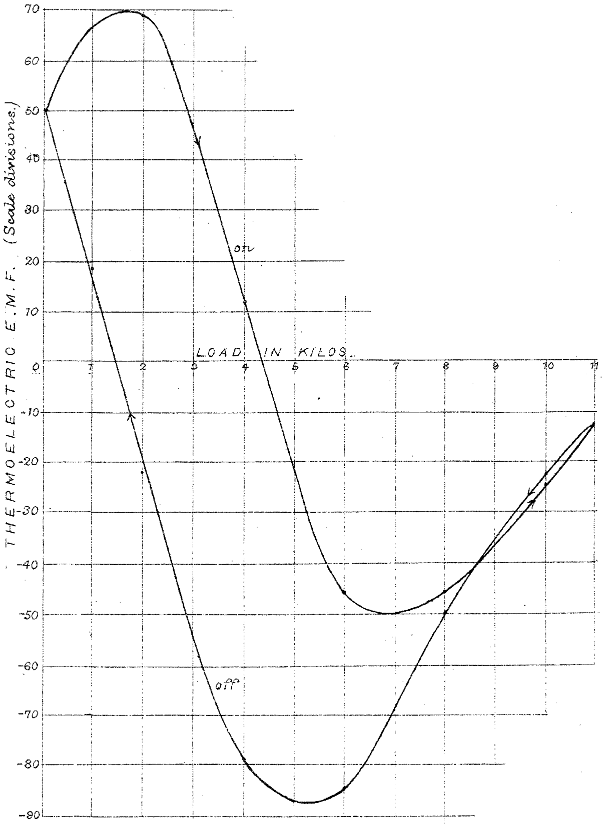


Fig. 12 (§ 22.)

Simultaneous changes of thermoelectric quality and of residual magnetism caused by applying and removing load.

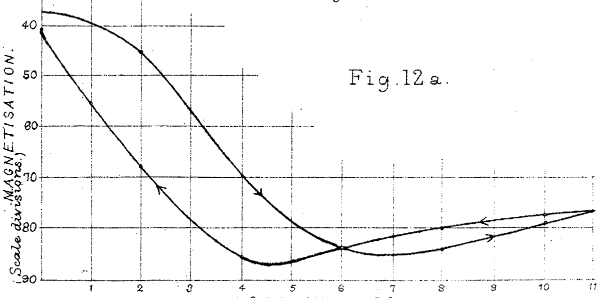
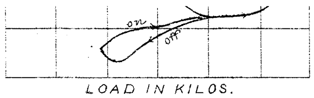
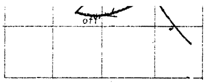


Fig. 12 a.


on
off
LOAD IN KILOS.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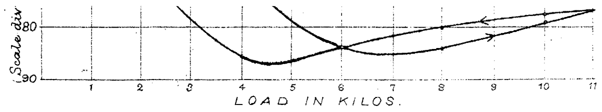
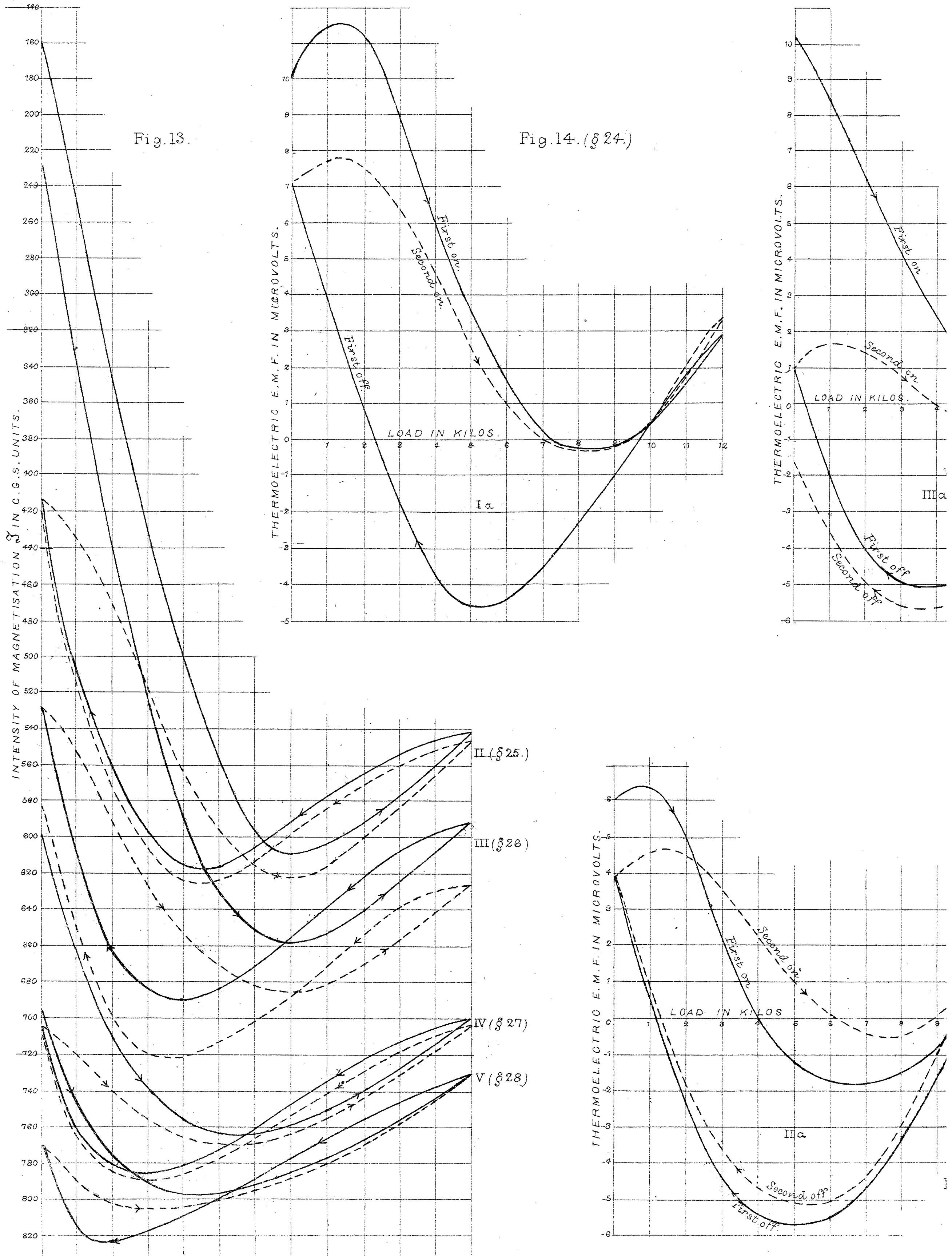


West, Newman & Co. sc.

Ewing.

EFFECTS OF STRESS ON MAGNETISM AND THERMOELECTRIC QUALIT

Effects of Stress on Thermoelectric Quality shown by
Corresponding effects on Magnetism shown b



C QUALITY IN VARIOUS CONSTANT MAGNETISING FIELDS.

hown by Curves Ia, IIa, IIIa, IVa, and Va.
shown by Curves II, III, IV, and V.

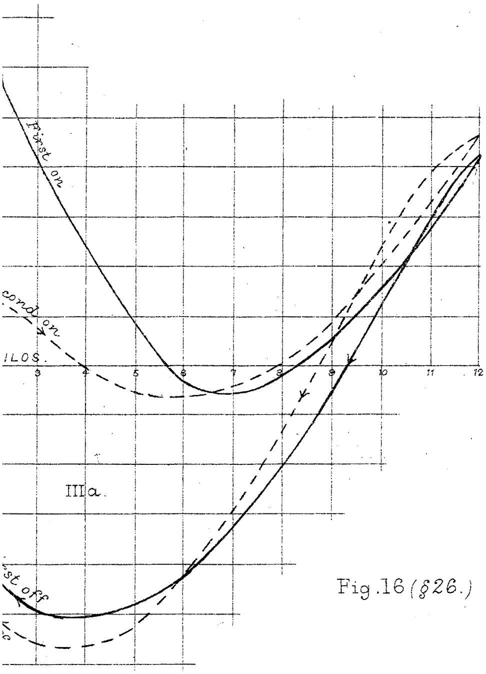


Fig. 16 (§ 26.)

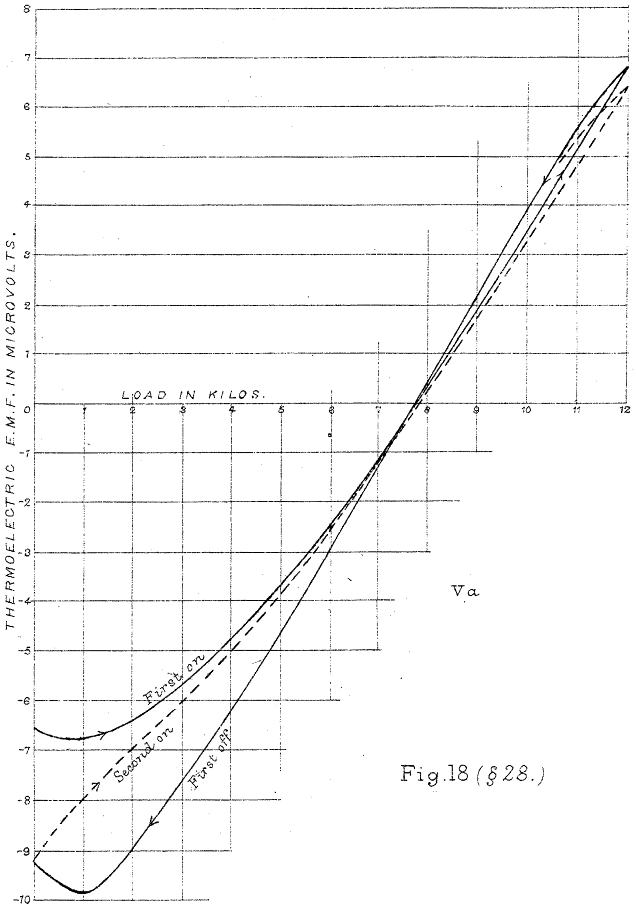


Fig. 18 (§ 28.)

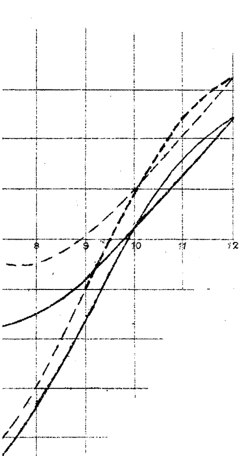


Fig. 15. (§ 25.)

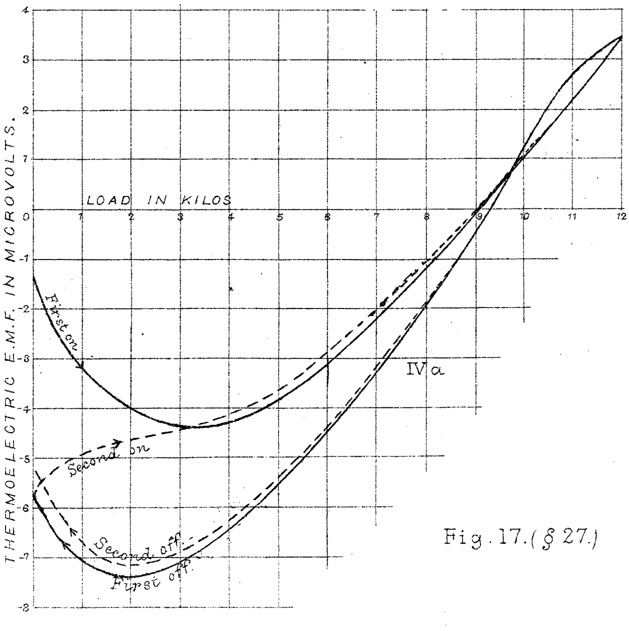
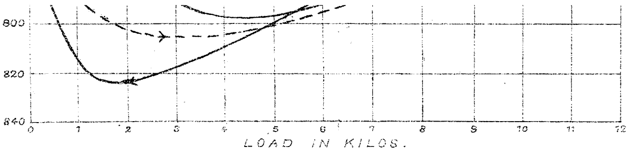
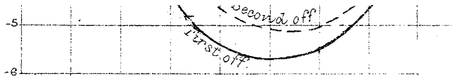
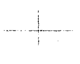
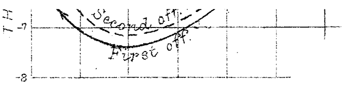


Fig. 17. (§ 27.)


800
820
840
0
1
2
3
4
5
6
7
8
9
10
11
12
LOAD IN KILOS.


-5
-6
Second off
First off





West, Newman & Co. sc.

Ewing.

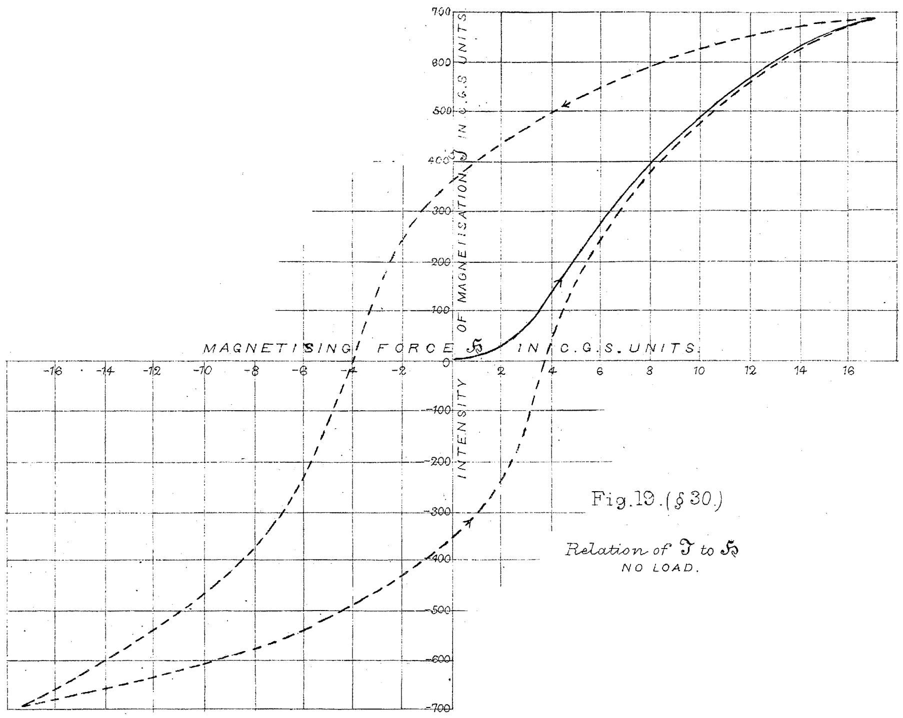
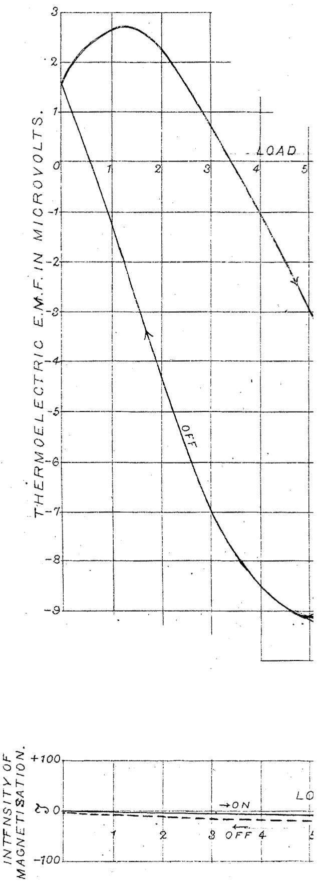


Fig.19.(§30.)

Relation of ℑ to ℌ
NO LOAD.



Fi

Relati

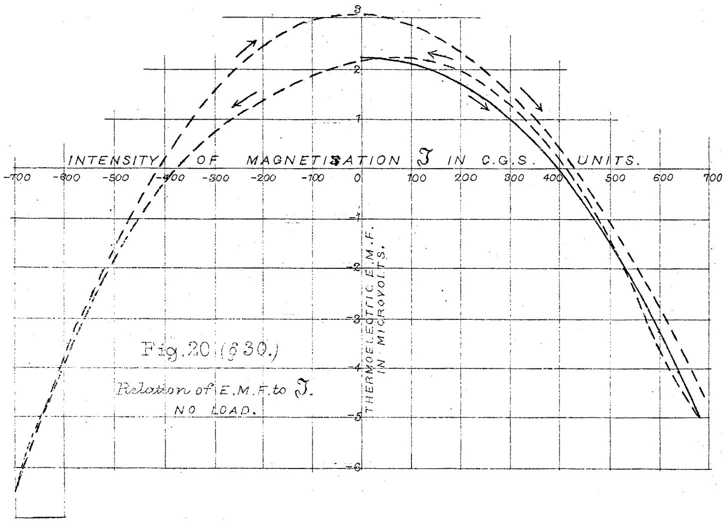


Fig.20.(§30.)

Relation of E.M.F. to ℑ.
NO LOAD.

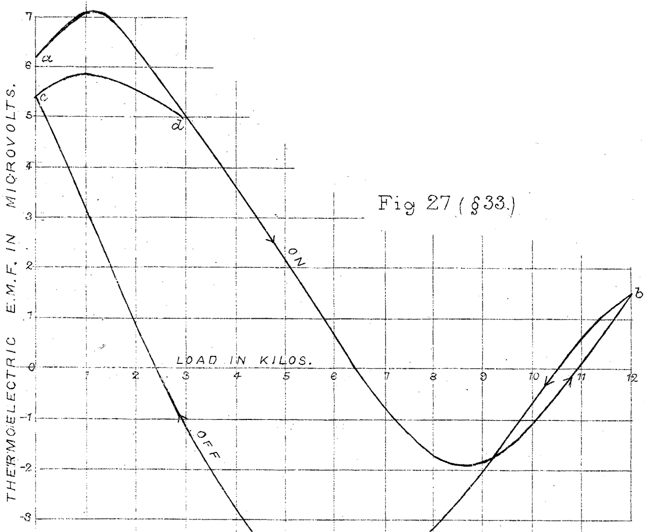
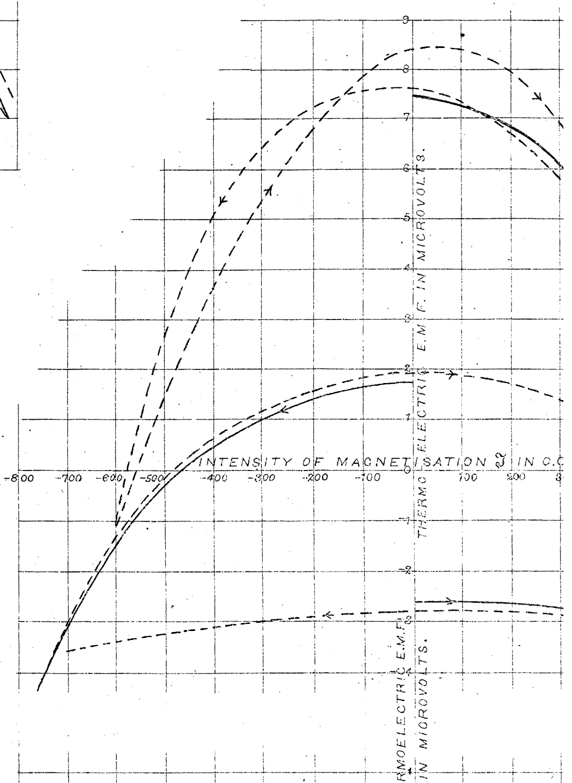


Fig 27 (§33.)



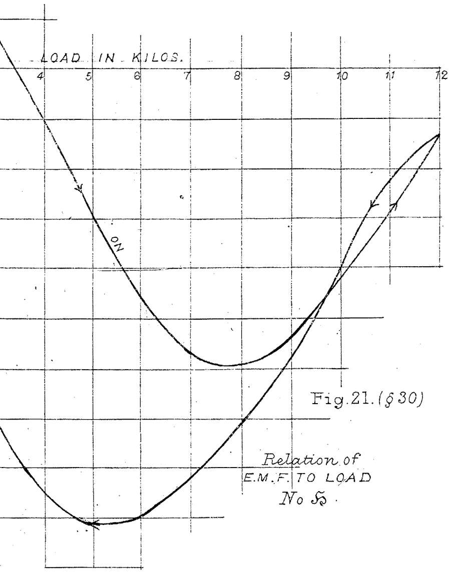


Fig.21.(§30)

Relation of E.M.F. TO LOAD No 5.

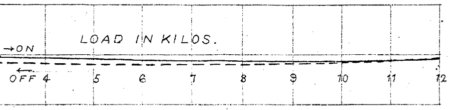


Fig.22 (§30)

Relation of ℑ to LOAD. No 5.

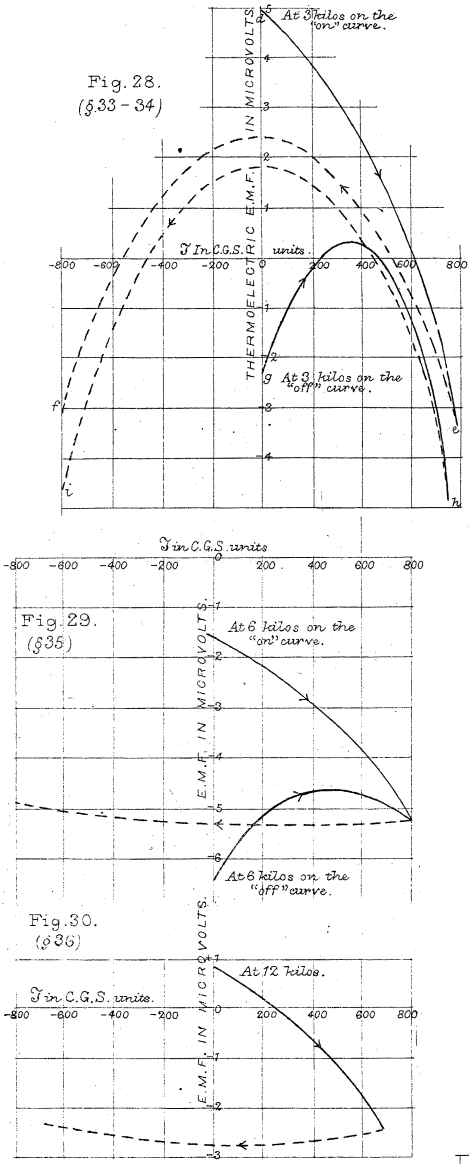
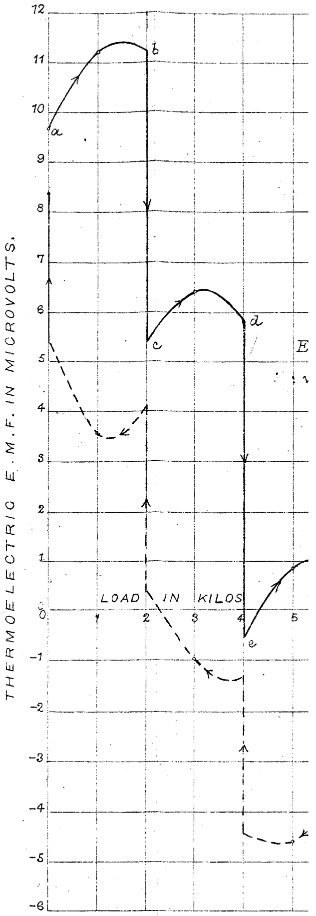


Fig. 28. (§33-34)

Fig. 29. (§35)

Fig. 30. (§36)

Figs. 28-30. Effects of Magnetisation on Thermoelectric Quality after applying Stress.



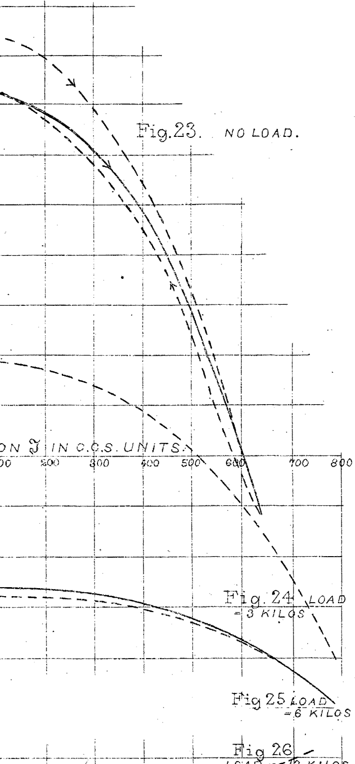


Fig.23. NO LOAD.

Fig. 24 LOAD = 3 KILOS

Fig 25 LOAD = 6 KILOS

Fig 26 LOAD = 12 KILOS

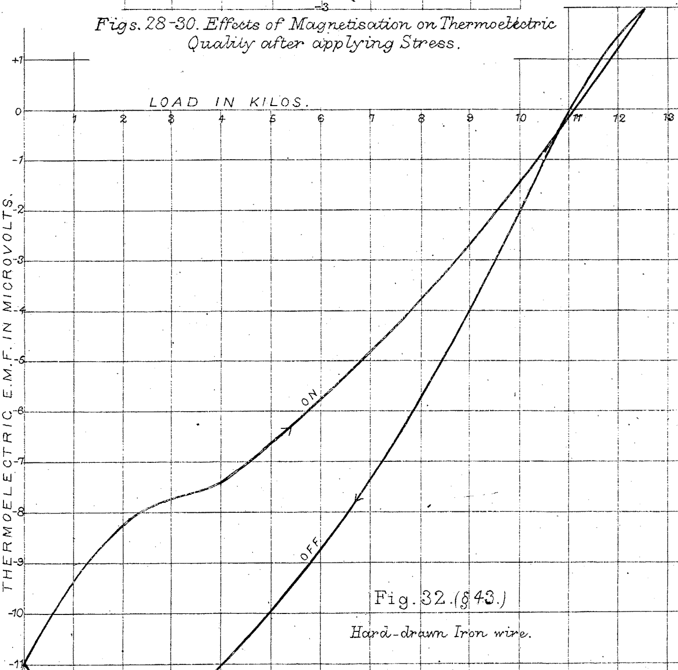
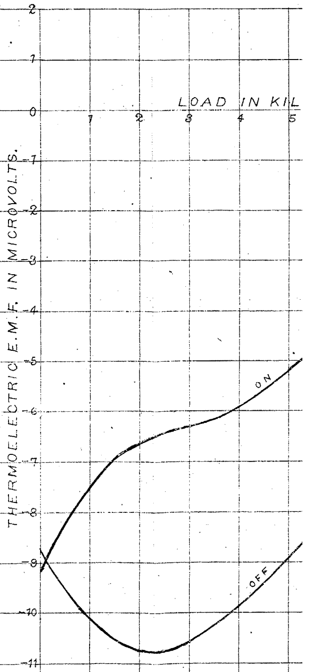


Fig. 32.(§43.)

Hard-drawn Iron wire.



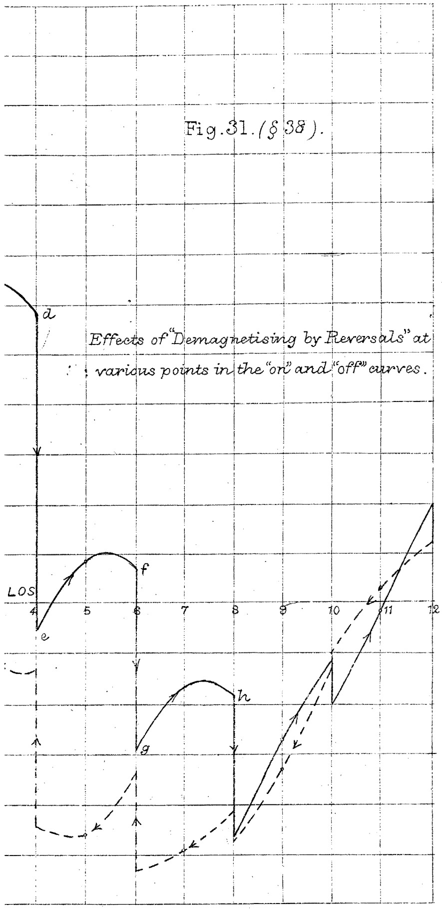


Fig. 31. (§ 38).

Effects of "Demagnetising by Reversals" at various points in the "on" and "off" curves.

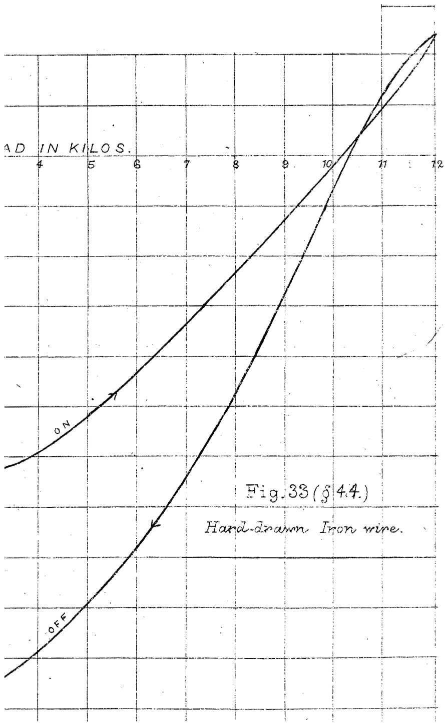
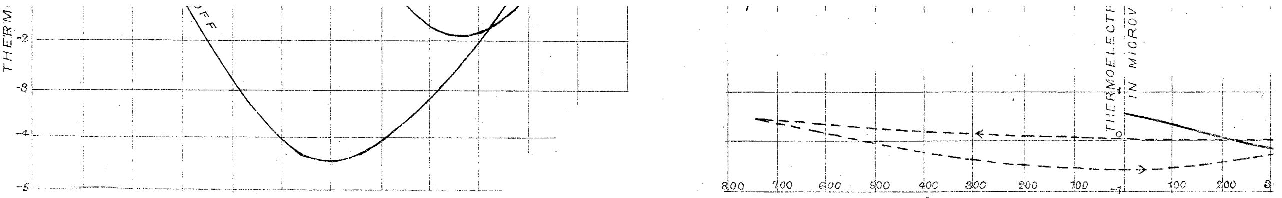


Fig. 33 (§ 44.)

Hard-drawn Iron wire.



Figs. 23 to 26, § 31. Effects of Magnetisi
Thermoelectric Quality under various Con

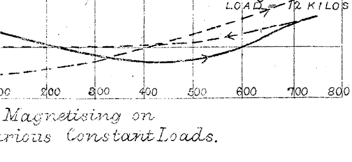


Fig 25 LOAD = 6 KILOS

Fig 26 LOAD = 12 KILOS

Magnetising on
rious Constant Loads.

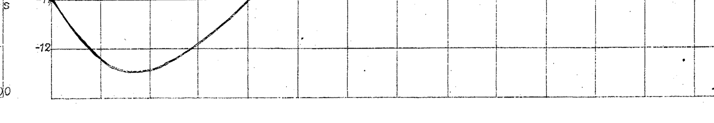
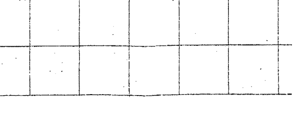
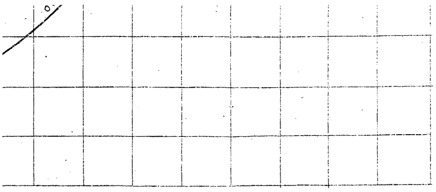


Fig. 32. (§ 43.)

Hard-drawn Iron wire.





West, Newman & Co. sc.

Fig. 1. (§6.)

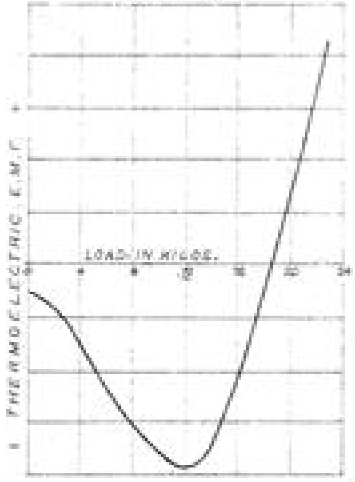


Fig. 2. (§7.)

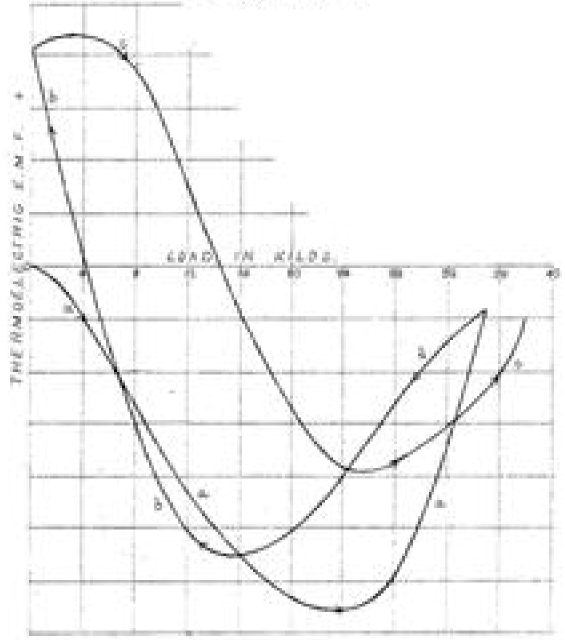


Fig. 3. (§8.)

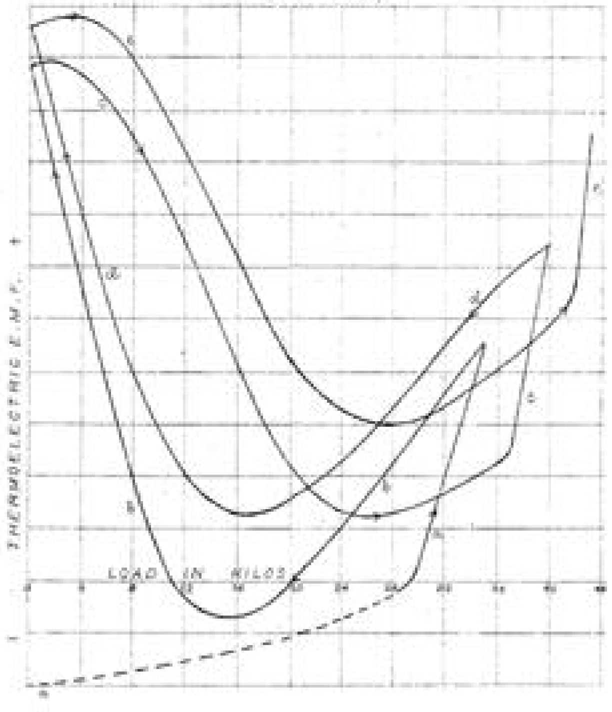
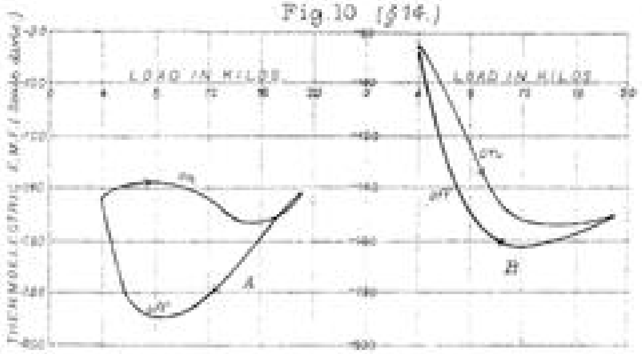


Fig. 10 (§14.)



Effects of vibration

A without vibration.
B with vibration.

Same wire, same cycle of loads.

Fig. 4. (§10.)

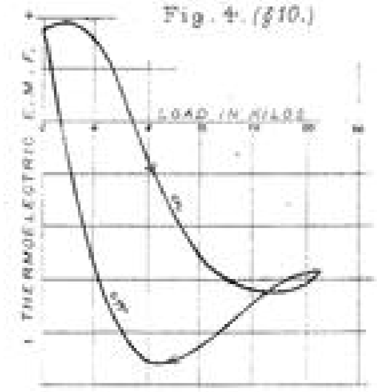


Fig. 5. (§12.)

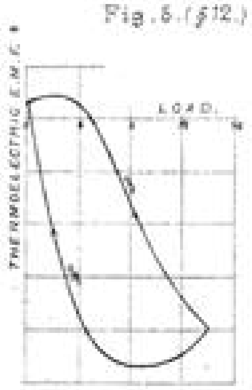
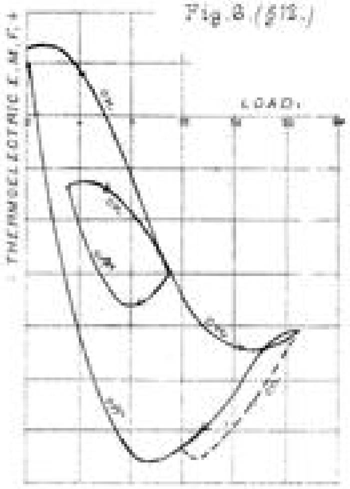


Fig. 6. (§12.)



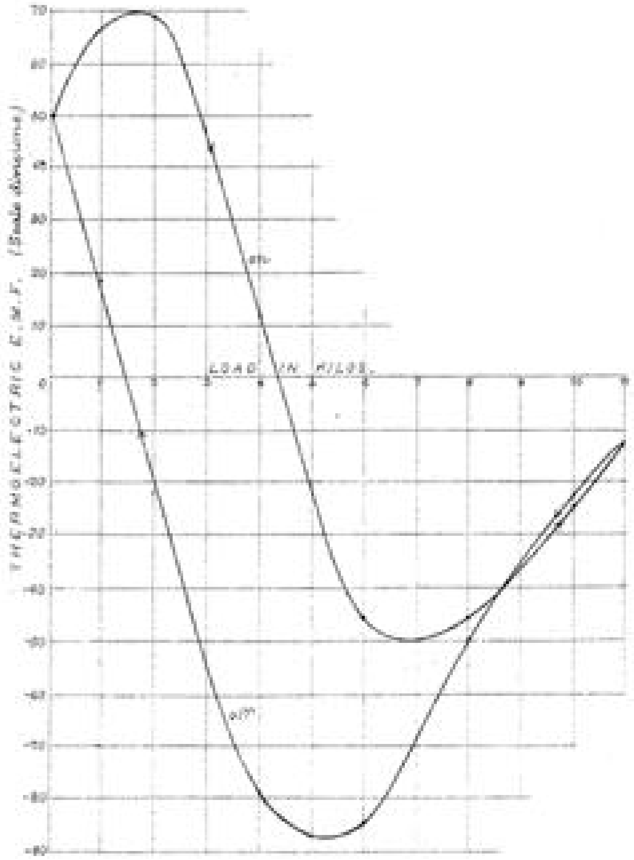


Fig. 12 (§22.)

Simultaneous changes of thermoelectric quality and of residual magnetism caused by applying and removing load.

Fig. 7. (§12.)

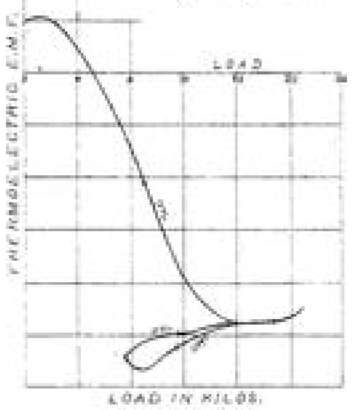


Fig. 8. (§12.)

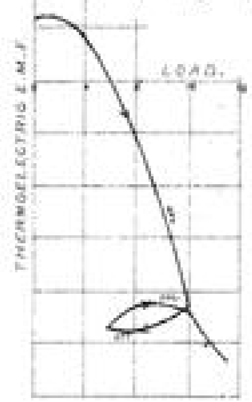


Fig. 9. (§12.)

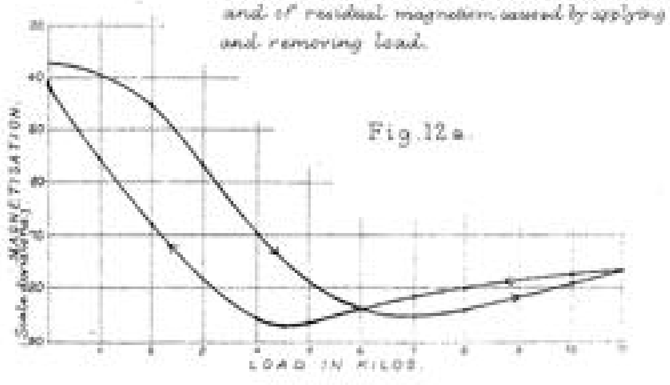


Fig. 12a.

West, Newman & Co. sc.

EFFECTS OF STRESS ON MAGNETISM AND THERMOELECTRIC QUALITY IN VARIOUS CONSTANT MAGNETISING FIELDS.

Effects of Stress on Thermoelectric Quality shown by Curves Ia, IIa, IIIa, IVa, and Va.
Corresponding effects on Magnetism shown by Curves II, III, IV, and V.

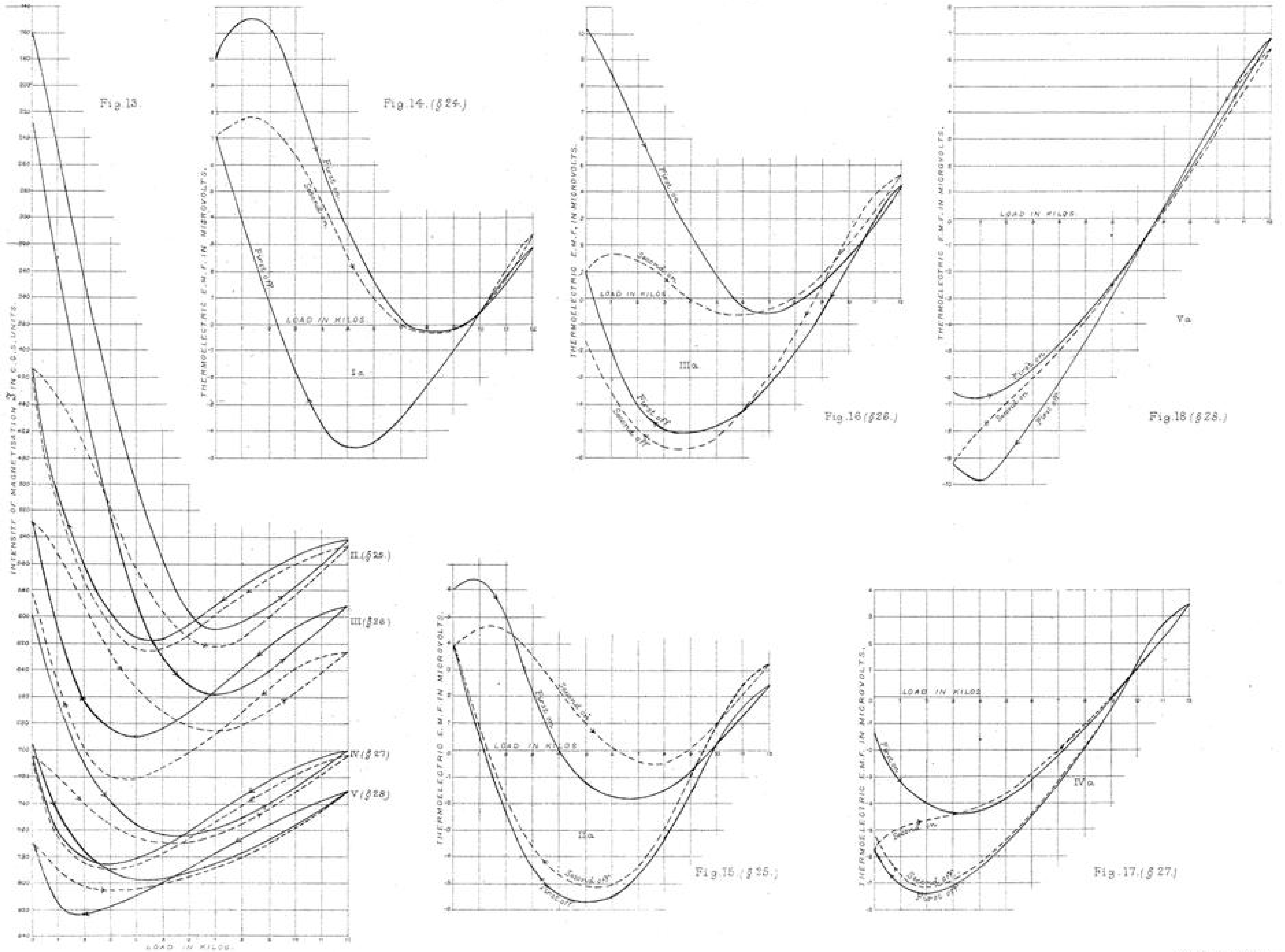


Fig. 13.

Fig. 14. (§ 24.)

Fig. 16 (§ 26.)

Fig. 18 (§ 28.)

Fig. 15. (§ 25.)

Fig. 17. (§ 27.)

West, Newman & Co. sc.

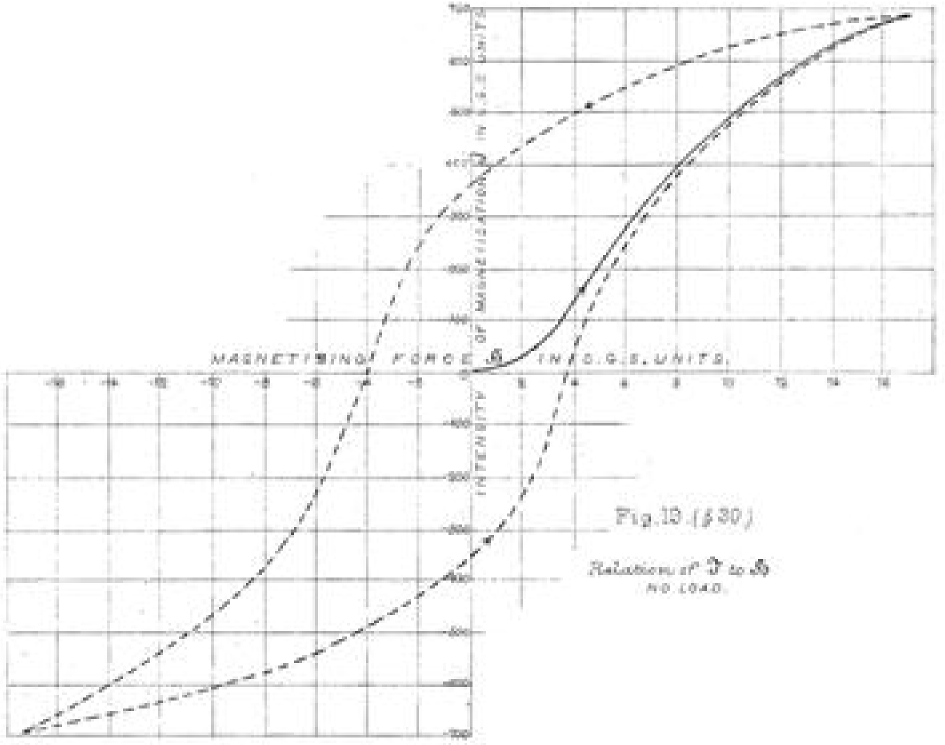


Fig. 19. (§ 30)

Relation of $\mathfrak{I}$ to $\mathfrak{H}$
NO LOAD.

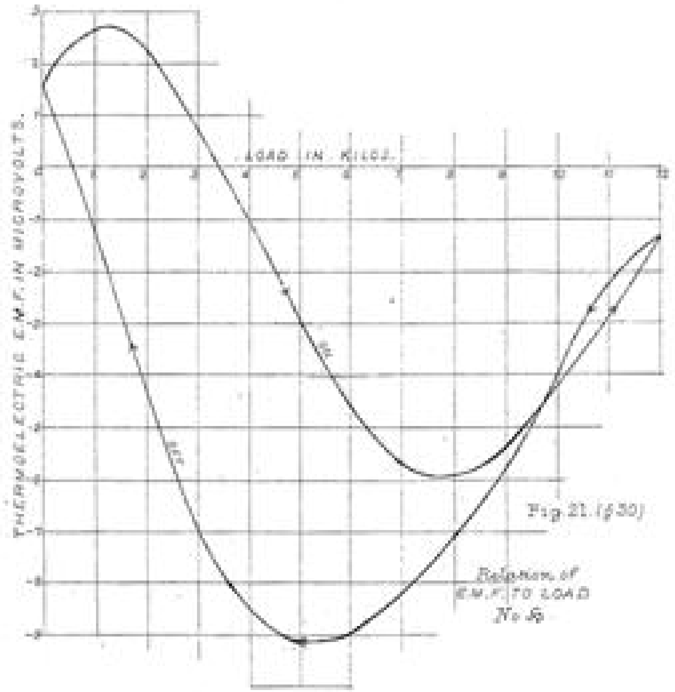


Fig. 21. (§ 30)

Relation of
E.M.F. TO LOAD
No $\mathfrak{H}$.

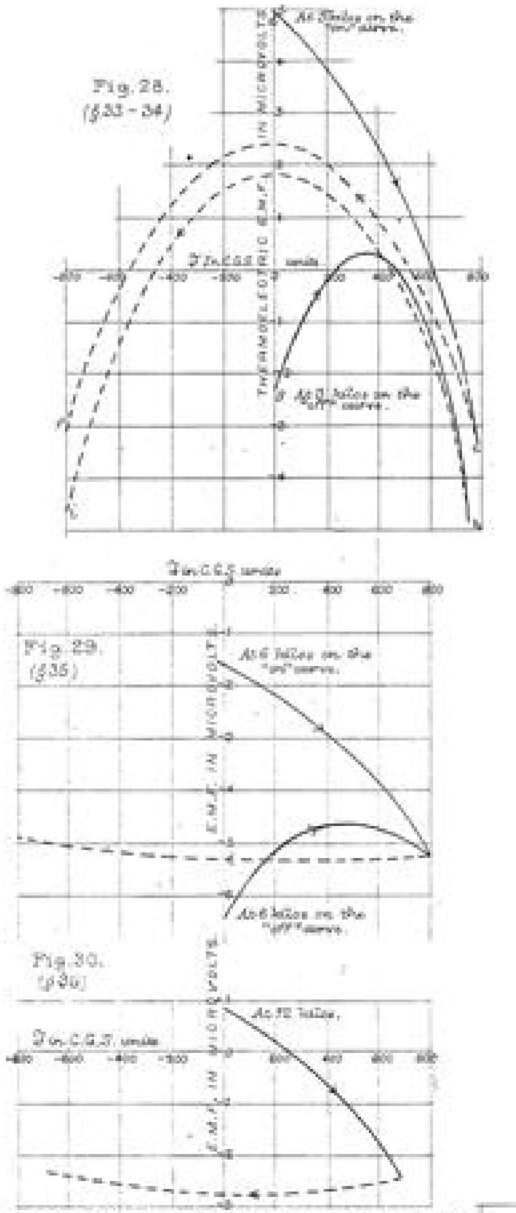


Fig. 28. (§ 33–34)

Fig. 29. (§ 35)

Fig. 30. (§ 36)

Figs. 28–30. Effects of Magnetisation on Thermoelectric Quality after applying Stress.

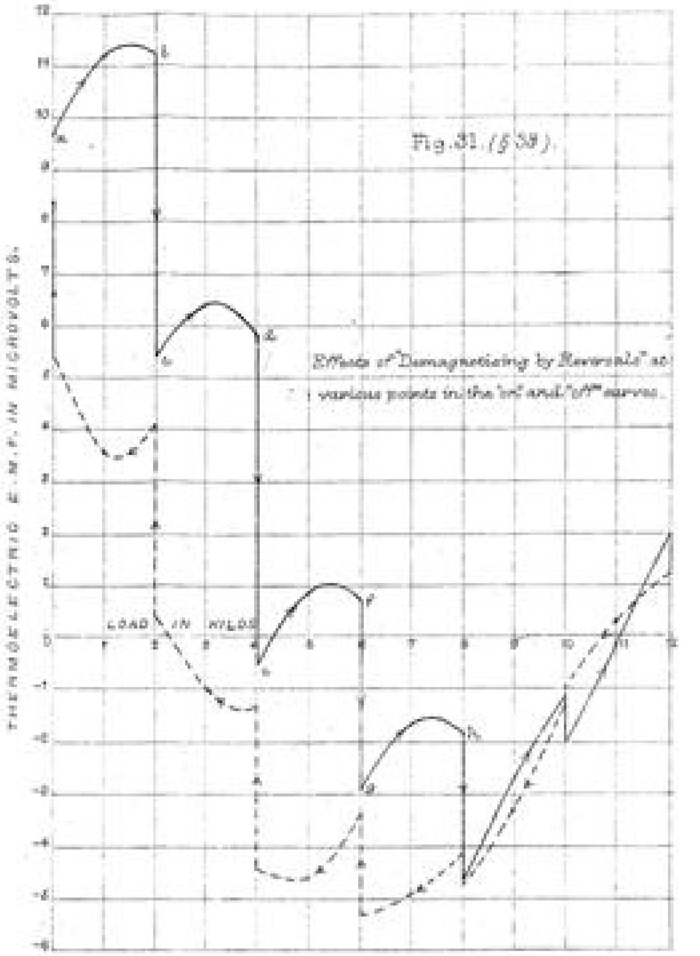


Fig. 31. (§ 39).

Effects of "Demagnetising by Reversals" at various points in the "on" and "off" curves.

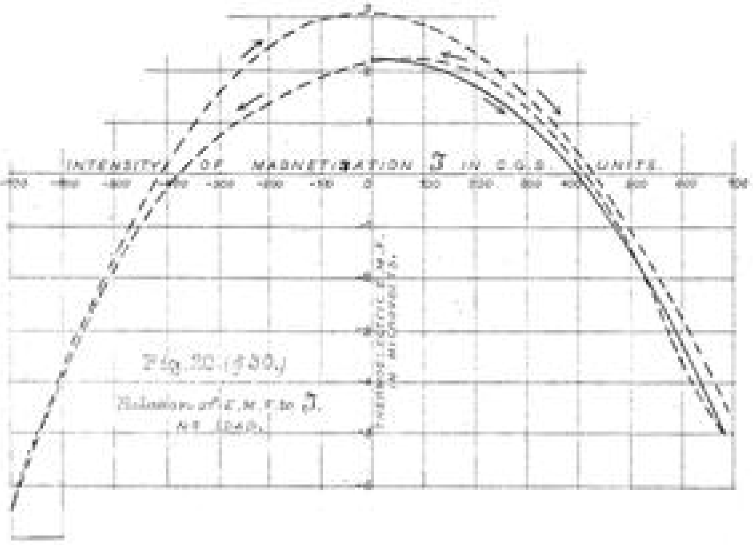


Fig. 20. (§ 30.)

Relation of E.M.F. to $\mathfrak{I}$.
NO LOAD.

Fig. 22 (§ 30)

Relation of $\mathfrak{I}$ to LOAD.
No $\mathfrak{H}$.

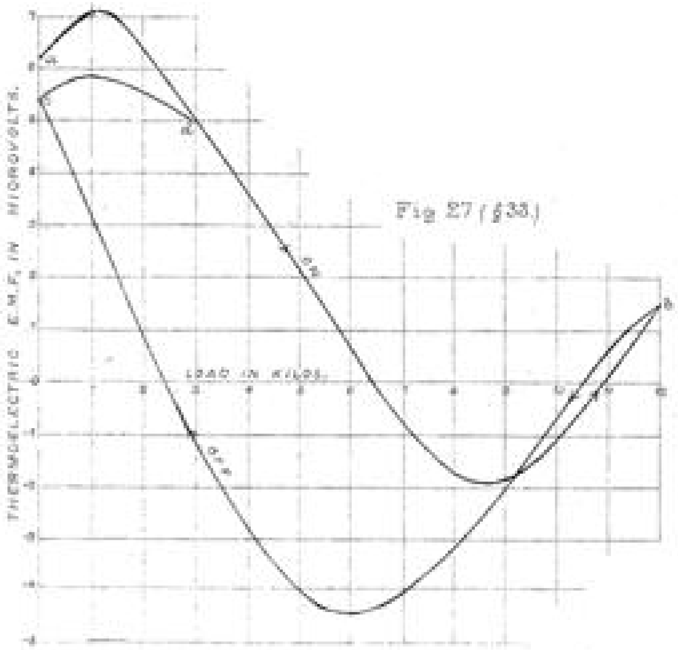


Fig. 27 (§ 38)

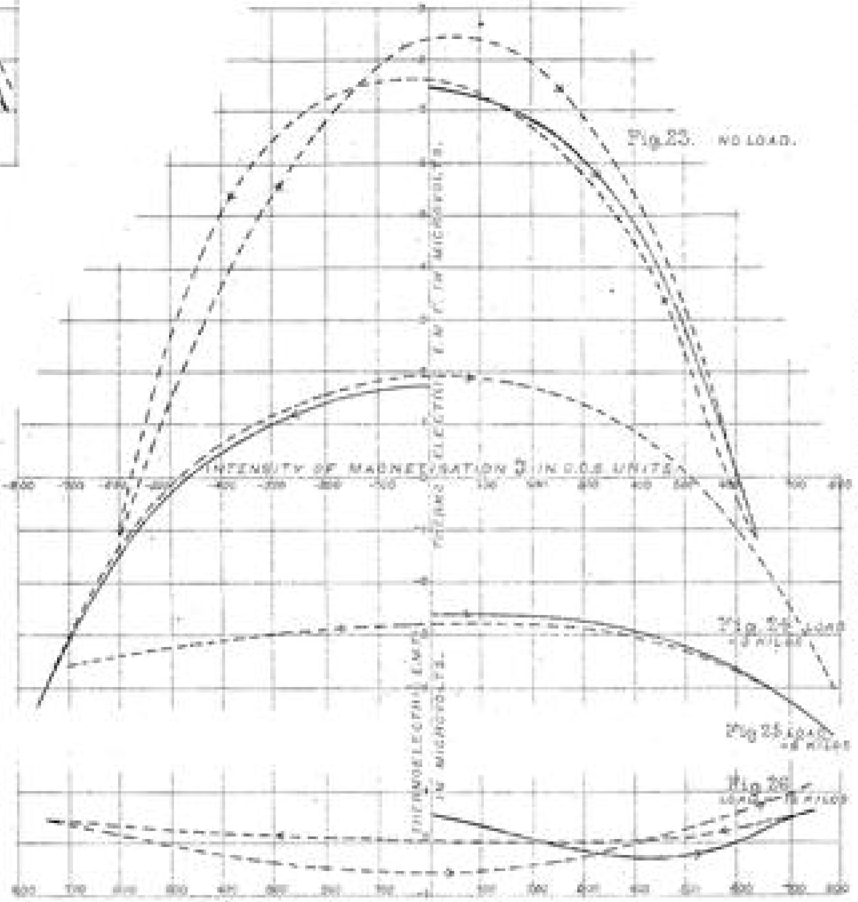


Fig. 23. NO LOAD.

Fig. 24. LOAD 3 KILOS.

Fig. 25. LOAD 6 KILOS.

Fig. 26. LOAD 12 KILOS.

Figs 23 to 26, § 31. Effects of Magnetising on Thermoelectric Quality under various Constant Loads.

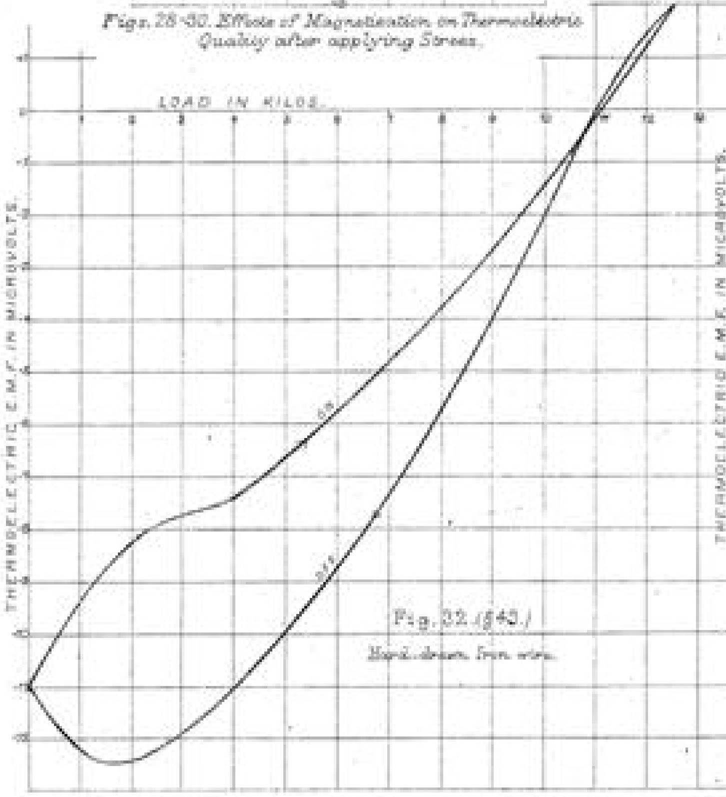


Fig. 32. (§ 43.)

Hard-drawn Iron wire.

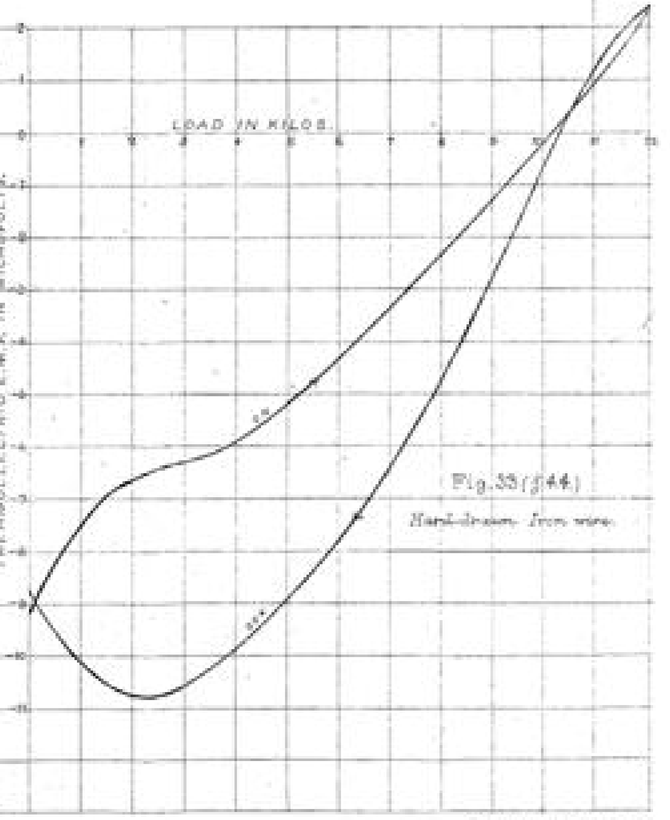


Fig. 33 (§ 44)

Hard-drawn Iron wire.

West, Newman & Co. sc.