XIV. *Magnetic and other Physical Properties of Iron at a High Temperature.*

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[PLATES 12–20.]

IT is well known that for small magnetising forces the magnetisation of iron, nickel, and cobalt increases with increase of temperature, but that it diminishes for large magnetising forces.* BAUER† has also shown that iron ceases to be magnetic somewhat suddenly, and that the increase of magnetisation for small forces continues to near the point at which the magnetism disappears. His experiments were made upon a bar which was heated in a furnace and then suspended within a magnetising coil and allowed to cool, the observations being made at intervals during cooling. This method is inconvenient for the calculation of the magnetising forces, and the temperature must have been far from uniform through the bar. In my own experiments‡ on an impure sample of nickel the curve of magnetisation is determined at temperatures just below the temperature at which the magnetism disappears, which we may appropriately call the critical temperature.

AUERBACH§ and CALLENDAR|| have shown that the electrical resistance of iron increases notably more rapidly than does that of other pure metals. BARRETT,¶ in announcing his discovery of recalescence, remarked that the phenomenon probably occurred at the critical temperature. TAIT** investigated the thermo-electric properties of iron, and found that a notable change occurred at a red heat, and thought it probable that this change occurred at the critical temperature.

It appeared to be very desirable to examine the behaviour of iron with regard to magnetism near the critical temperature, and to ascertain the critical temperatures

* ROWLAND, 'Phil. Mag.,' Nov., 1874.
† 'WIEDEMANN, Annalen,' vol. 11, 1880.
‡ 'Roy. Soc. Proc.,' June, 1888.
§ 'WIEDEMANN, Annalen,' vol. 5, 1878.
|| 'Phil. Trans.,' A, 1887.
¶ 'Phil. Mag.,' Jan., 1874.
** 'Edinburgh Roy. Soc. Trans.,' Dec., 1873.

for different samples. It also appeared to be desirable to trace the resistance of iron wire up to and through the critical temperature, and to examine more particularly the phenomenon of recalescence, and determine the temperature at which it occurred.

The most interesting results at which I have arrived may be shortly stated as follows :—

For small magnetising forces the magnetisation of iron steadily increases with rise of temperature till it approaches the critical temperature, when it increases very rapidly, till the permeability in some cases attains a value of about 11,000. The magnetisation then very suddenly almost entirely disappears.

The critical temperatures for various samples of iron and steel range from 690° C. to 870° C.

Heating iron a little above the critical temperature does not entirely wipe out all effects of previous magnetisation.

The temperature coefficient of electrical resistance is greater for iron than for other metals; it increases greatly with increase of temperature till the temperature reaches the critical temperature, when it suddenly changes to a value more nearly approaching to other metals. Recalescence does occur at the critical temperature. The quantity of heat liberated in recalescence has been measured and is found to be quite comparable with the heat required to melt bodies.

Since making the experiments and writing the preliminary notes which have already appeared in the 'Proceedings of the Royal Society,' my attention has been called to two papers which deal in part with some of the matters on which I have been experimenting. PIONCHON* has shown that the specific heat of iron is very much greater at a red heat than at ordinary temperatures. W. KOHLRAUSCH,† in an interesting paper, shows that, whereas the temperature coefficient of resistance of iron is much greater than usual for temperatures below the critical temperature, it suddenly diminishes on passing that temperature. He also identifies the temperature of recalescence with the critical temperature. So far as resistance of iron is concerned, W. KOHLRAUSCH has anticipated my results, which I give, however, for the sake of completeness.

Magnetic Experiments.

The method of performing the magnetic experiments was the same as that used by ROWLAND. The copper wire was, however, insulated carefully with asbestos paper laid over the wire, and with layers of asbestos paper between the successive layers of the wire. The insulation resistance between the primary and the secondary coils was always tested, both at the ordinary temperature and at the maximum temperature used. At the ordinary temperature this resistance always exceeded a megohm; at

* 'Comptes Rendus,' vol. 103, p. 1122.

† 'WIEDEMANN, Annalen,' vol. 33, 1888.

the maximum temperature it exceeded 10,000 ohms, and generally lay between 10,000 and 20,000 ohms. The ring to be examined, with its coils of copper wire, was placed in a cylindrical cast-iron box, and this in a Fletcher gas furnace, the temperature of which was regulated by the supply of gas. The temperatures were estimated by the resistance of the secondary coil. It was observed that the resistance of this coil at the ordinary temperature increased slightly after being raised to a high temperature; this I attribute to oxidation of the wire where it leaves the cast-iron box. However, it introduced an element of uncertainty into the determination of the actual temperatures, amounting, perhaps, to 20° C. at the highest temperature. This error will not affect the differences between neighbouring temperatures, with which we are more particularly concerned.

The resistance of the ballistic galvanometer is 0·43 ohm; to this additional resistances were added to give the necessary degree of sensibility. The ratio of two successive elongations of the galvanometer is $(1 + r)/1 = 1{\cdot}12/1$. The time of oscillation T and the sensibility varied a little during the experiments, but so little, that the correction would fall within the limits of errors of observation in these experiments.

The total induction $= \left\{\left(1 + \frac{r}{2}\right)\frac{\mathrm{C}}{\alpha}\frac{\mathrm{T}}{2\pi}\right\}\frac{1}{2n}\,\mathrm{R.A.}10^8$, where C is the current which gives the deflection α, n is the number of turns in the secondary coil, R the resistance of the secondary circuit, A the mean of the first and second elongations on reversal of the current in the primary.

The magnetising force $= 4\pi mc/l$, where m is the number of turns in the primary, l the mean length of lines of force in the ring, c the current in absolute measure in the primary.

With my galvanometer as adjusted, a Grove's cell, the E.M.F. of which was at the time determined to be 1·800 volt, gave a deflection of 158·5 divisions through a resistance of 50,170 ohms, whence

$$\frac{\mathrm{C}}{\alpha} = \frac{1{\cdot}800}{158{\cdot}5 \times 50{,}170} = 0{\cdot}0000002264,$$

$$\mathrm{T} = 13{\cdot}3.$$

Hence

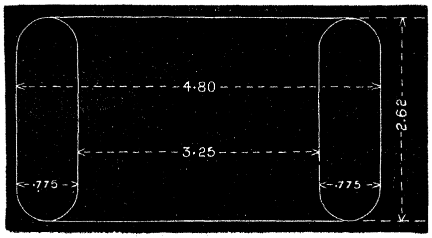
$$\left(1 + \frac{r}{2}\right)\frac{\mathrm{C}}{\alpha}\frac{\mathrm{T}}{2\pi} = 5{\cdot}09 \times 10^{-7}.$$

The ring method of experiment is open to the objection that the magnetising force is less in the outer than in the inner portions of the ring. The results, in fact, give the average results of forces which vary between limits.

Wrought Iron.—The sample of wrought iron was supplied to me by Messrs.

MATHER and PLATT. I have no analysis of its composition. I asked for the softest iron they could supply.*

The dimensions of the ring were as shown in the accompanying sketch :—



The area of section is 1·905 sq. cm. The area of the middle line of the secondary coil is estimated to be 2·58 sq. cms. This estimate is, of course, less accurate than the area of section of the ring itself.

The secondary coil had 48 convolutions, the primary 100 convolutions.

At the beginning of the experiments the insulation resistance of the secondary from the primary was in excess of 1 megohm; the resistance of the secondary and the leads was 0·692, the temperature being 8°·3 C.

The resistance of the leads to the secondary and of the part of the secondary external to the furnace was estimated to be 0·04.

A curve of magnetisation was determined at the ordinary temperature on the virgin sample with the following results, shown graphically in Curve I.; in each case the observation was repeated twice with reversed direction of magnetising currents, and the kicks in the galvanometer were found to agree very closely together :—

Magnetising force .	0·15	0·3	0·6	1·2	2·2	4·4	8·2	14·7	24·7	37·2	69·2
Induction per sq. cm.	39·5	116	329	1,560	6,041	10,144	12,633	14,059	14,702	15,149	15,959

The ring was next heated and observations were made with a magnetising force of 8·0 to ascertain roughly the point at which the magnetism disappeared. After the magnetism had practically disappeared and the temperature was roughly constant, as indicated by the resistance, being 2·92 before the experiment and 2·85 after the experiment, corresponding with temperatures of 838° C. and 812° C., the induction was determined for varying magnetising forces.

Magnetising force . . .	2·4	4·2	8·0	21·0	49·8
Total induction	small	12·3	22·7	58·2	143

This shows that the induction is, so far as the experiment goes, proportional to the inducing force.

Taking the total induction as 143, corresponding to a force of 49·8, we have

* [*Added July* 2, 1889.—Sir JOSEPH WHITWORTH and Co. have since kindly analysed this sample for me with the following result :—

	C	Mn	S	Si	P	Slag†
Per cent. . . .	·010	·143	·012	Nil	·271	·436

† Containing 74 per cent. SiO_2 (Silica).]

induction in the iron 109, or 57 per sq. cm., giving permeability equal to 1·14, showing that the material has suddenly become non-magnetic.

The ring was now allowed to cool, some rough experiments being made during cooling. When cold the resistance of the secondary and the leads was found to be 0·697 ohm. The ring was again heated till the resistance of the secondary reached 2·845 and the magnetism had disappeared. It was next allowed to cool exceedingly slowly, and the following observations were made with a magnetising force of 0·075 C.G.S. unit:—

Resistance of secondary . .	2·81	2·80	2·79	2·78	2·765
Temperature	796°	792°	788°	785°	781°
Induction per sq. cm. . . .	0	0	0	126·8 (2·78 to 2·765)	

showing that magnetisation returns at a temperature corresponding to resistance between 2·78 and 2·765.

Systematic observations then began. The results are given in the following tables and the curves to which reference is made. The curves are in each case set out to two scales of abscissæ, the better to bring out their peculiarities.

Tables 1–4.

	Table 1, Curve II.	Table 2, Curve III.	Table 3, Curve IV.	Table 4, Curve V.
Resistance of secondary before experiment	2·76	2·75	2·72	2·67
Temperature of secondary before experiment	778° C.	775° C.	763° C.	744° C.
Resistance of secondary after experiment	2·75	2·73	2·695	2·66
Temperature of secondary after experiment	775° C.	767° C.	754° C.	741° C.

Table 1: Magnetising force.	Table 1: Induction per sq. cm.	Table 2: Magnetising force.	Table 2: Induction per sq. cm.	Table 3: Magnetising force.	Table 3: Induction per sq. cm.	Table 4: Magnetising force.	Table 4: Induction per sq. cm.
0·075	511·8	0·075	494	0·075	{328, 260}	0·075	{227, 180}
0·15	1313·9	0·15	1033	0·15	{710, 635}	0·15	{473, 425}
0·3	2482·6	0·30	3286	0·3	2304	0·3	{1281, 1172}
0·6	3257·4	0·6	4520	0·6	5281	0·6	5377
1·2	3659·2	1·2	5367	1·2	6544	2·2	8165
2·4	4104·0	2·4	5668	2·2	7318	7·6	9295
4·4	4520·0	4·2	6056	7·6	8036	47·2	9781
		7·8	6228	13·0	8323		
		12·8	6587	46·6	8581		
		45·2	6945				

TABLES 5–8.

	Table 5, Curve VI.	Table 6, Curve VII.	Table 7, Curve VIII.	Table 8, Curve IX.
Resistance of secondary before experiment	2·61	2·47	2·29	2·0
Temperature of secondary before experiment	722° C.	670° C.	603° C.	494° C.
Resistance of secondary after experiment	2·61	2·47	2·21	1·94
Temperature of secondary after experiment	722° C.	670° C.	573° C.	472° C.

Table 5: Magnetising force.	Table 5: Induction per sq. cm.	Table 6: Magnetising force.	Table 6: Induction per sq. cm.	Table 7: Magnetising force.	Table 7: Induction per sq. cm.	Table 8: Magnetising force.	Table 8: Induction per sq. cm.
0·075	163 / 125	0·075	77	0·075	68 / 50	0·075	54·7 / 35·8
0·15	305 / 278	0·15	162	0·15	128 / 108	0·15	98 / 75
0·30	762 / 726	0·3	427	0·30	307 / 275	0·3	245 / 195
0·6	4,004	0·6	1,516	0·60	908 / 834	0·6	742 / 590
2·2	8,952 / 8,895	2·2	9,381	2·2	9,604	2·2	9,433
7·6	10,410	7·6	11,562	7·6	11,992	7·6	12,273
47·2	11,224 / 11,111	47·8	12,859	50·6	14,470	53·5	15,201

At this stage the ring was allowed to cool down, and on the following day a determination was made of the curve at ordinary temperature of 9°·6 C. (Curve X.)

Magnetising force	0·075	0·15	0·3	0·6	1·2	2·2	4·0	6·8	11·4	17·3	57·0
Induction per sq. cm.	21·6 / 13·0	41·1 / 32·0	116 / 93	308 / 273	1,482	6,912	10,341	12,410	13,640	14,255	15,623

The ring was next heated till the resistance reached about 2·4, was allowed to cool somewhat, and a curve was determined (Curve XI.) at a resistance of 1·69 to 1·64. Temperature 378° C. to 354° C.

Magnetising force	0·075	0·15	0·3	0·6	1·2	2·2	4·0	7·6	13·1	51·7
Induction per sq. cm.	38 / 44	93 / 101	263	874	4,288	8,818	11,296	12,589	13,404	15,174

In addition to the variation of magnetisability depending on the temperature, these numbers show one or two interesting facts. Where two observations are given these are the results of successive reversals in opposite directions. After each experiment the ring was demagnetised by reversals of current ; thus currents successively diminishing in amount were passed through the primary, each current being reversed

ten times. The last currents gave magnetising forces 1·2, 0·6, 0·3, 0·15, 0·075, 0·05. The inequality of successive observations is due to the residual effect of the current last applied ; it is remarkable to observe how greatly this small force affects the result. In Curve XI. the first deflection was caused by a reversal of a current opposite to the last demagnetising current.

Comparing Curves X. and I. we see that the effect of working with the sample is to diminish its magnetisability for small forces, a fact which will be better brought out later.

Referring now to the temperature effects, we see that as the temperature rises the steepness of the initial part of the curve increases, but the maximum magnetisation diminishes. The coercive force, that is, the force required to completely demagnetise the material after it has been exposed to a great magnetising force, also, judging from the form of the ascending curves, diminishes greatly.

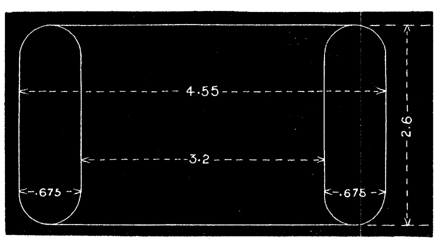
In Curves XII., XIII., and XIV. the abscissæ are temperatures, and the ordinates are induction-magnetising force, called by Sir WILLIAM THOMSON the permeability, and usually denoted by μ. These curves correspond to constant magnetising forces of 0·3, 4·0, 45·0. They best illustrate the facts which follow from these experiments. Looking at the curve for 0·3, we see that the permeability at the ordinary temperature is 367 ; that as the temperature rises the permeability rises slowly, but with an accelerated rate of increase ; above 681° C. it increases with very great rapidity, until it attains a maximum of 11,000 at a temperature of 775° C. Above this point it diminishes with extreme rapidity, and is practically unity at a temperature of 786° C.

Regarding the iron as made up of permanently magnetic molecules, the axes of which are more or less directed to parallelism by magnetising force, we may state the facts shown by the curve by saying that rise of temperature diminishes the magnetic moment of the molecules gradually at first, but more and more rapidly as the critical temperature at which the magnetism disappears is approached, but that the facility with which the molecules have their axes directed increases with rise of temperature at first slowly, but very rapidly indeed as the critical temperature is approached.

Whitworth's Mild Steel.—This sample was supplied to me by Sir JOSEPH WHITWORTH and Co., who also supplied me with the following analysis of its composition :—

	C	Mn	S	Si	P
Per cent. . .	·126	·244	·014	·038	·047

The dimensions of the ring were as shown in the accompanying sketch.



The area of section of the ring is 1·65 sq. cm. The area of the middle line of the secondary coil is estimated to be 2·32 sq. cms.

The secondary coil had 56, the primary 98, convolutions.

The resistance of the secondary and leads was 0·81 at 12° C.

The ring was at once raised to a temperature at which it ceased to be magnetic; with a magnetising force of 32·0, the total induction was observed to be 80·8, giving the value of the permeability 1·12.

The insulation resistance between the primary and the secondary was observed to be 12,000 ohms.

The ring was now allowed to cool very slowly; at resistance of 3·00, corresponding to a temperature of 723° C., the ring was non-magnetic; at 2·99, corresponding to 720° C., it was distinctly magnetic.

The following five series of observations were made at descending temperatures, the means of two observations being in each case given; the sample was demagnetised by reversals after each experiment:—

TABLES 9–13.

	Table 9, Curve XV.	Table 10, Curve XVI.	Table 11, Curve XVII.	Table 12, Curve XVIII.	Table 13, Curve XIX.
Resistance at beginning of experiment	2·99	2·71	2·31	1·80	0·812
Temperature at beginning of experiment	721° C.	630° C.	500° C.	333° C.	12° C.
Resistance at end of experiment	2·95	2·75	2·245	1·80	0·812
Temperature at end of experiment	708° C.	645° C.	478° C.	333° C.	12° C.

Table 9: Magnetising force.	Table 9: Induction per sq. cm.	Table 10: Magnetising force.	Table 10: Induction per sq. cm.	Table 11: Magnetising force.	Table 11: Induction per sq. cm.	Table 12: Magnetising force.	Table 12: Induction per sq. cm.	Table 13: Magnetising force.	Table 13: Induction per sq. cm.
0·075	607	0·075	140	0·075	77	0·075	73	0·075	19
0·15	1214	0·15	295	0·15	161	0·15	125	0·15	48
0·3	2031	0·3	1,098	0·30	396	0·30	293	0·3	119
0·6	2698	0·6	4,175	0·60	1,847	0·6	813	0·6	312
1·2	3181	1·2	6,163	1·2	5,217	1·2	4,552	0·9	884
2·2	3607	2·1	8,122	2·1	7,642	2·1	7,840	1·7	5,087
7·6	4118	7·5	10,900	7·7	11,586	7·4	12,232	3·3	9,535
36·9	4800	38·0	12,074	40·4	14,816	42·6	15,180	6·1	12,387
								10·7	13,991
								45·0	16,313

The following experiment is instructive, as showing a phenomenon which constantly recurs, namely, that after not quite perfect demagnetisation, as above described, the first kick of the galvanometer being in the same direction as the last magnetising force, the first kick is very materially greater than the reverse kick for small magnetising forces, is somewhat less for medium forces, and about the same for great forces. I have no explanation of this to offer.

The ring was heated until the resistance of the secondary coil was about 2·4, corresponding to a temperature of 529° C. Currents successively diminishing in amount were then passed through the primary, each current being reversed ten times. The last currents gave magnetising forces 1·2, 0·6, 0·3, 0·15, 0·075, and 0·05, the intention being to demagnetise the sample. The ring was allowed to cool till the resistance of secondary was 2·0, corresponding to a temperature of 398° C. The following series of observations was made: the first kick was in all cases produced by a reversal of current from the direction of the last demagnetising current; the second kick by a reversal in the opposite sense.

TABLE 14.

Magnetising force.	Galvanometer kick.	Resistance in circuit.
0·075	{ 20·5 13·5 }	12·43
0·15	{ 41·5 32·5 }	,,
0·3	{ 104·0 81·0 }	,,
0·6	{ 284·5 241·0 }	,,
1·2	{ 143·5 150·0 }	102·43
2·1	{ 262·5 265·0 }	,,
4·0	{ 351·0 351·0 }	,,
7·3	{ 210·0 211·5 }	202·43
12·1	{ 235·5 234·0 }	,,
43·4	{ 272·5 271·5 }	,,

The resistance of the secondary coil at the end of the experiment was 2·05; temperature, 415° C.

The sample was again heated until it became non-magnetic, and then allowed to cool very slowly, and the following series of observations were made, the ring being demagnetised as before after each series. The actual kicks of the galvanometer are

given, as they illustrate further the point last mentioned. In the first two series only one kick was taken, to save time.

TABLE 15.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.	Resistance of coil.	Temperature.
					° C.
				3·025	733
0·075	64·5	3·455	61		
0·15	287·0	3·454	273		
0·3	244·0	13·453	903		
0·6	199·0	23·452	1286		
1·2	241·0	23·451	1554		
2·0	290·0	23·450	1870		
				3·019	731

TABLE 16.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.	Resistance of coil.	Temperature.
					° C.
				3·018	730
0·075	133	13·448	492		
0·15	305	13·448	1128		
0·3	302	23·448	1948		
0·6	91	103·449	2584		
1·2	95	103·449	2698		
37·4	137	103·449	2891		
				3·019	731

TABLE 17.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.	Resistance of coil.	Temperature.
					° C.
				3·018	730
0·075	214	13·448	792		
0·075	149	13·447	551		
0·075	145	13·445	536		
0·6	102	103·444	2897		
38·4	150	103·442	4260		
				3·012	729

TABLE 18.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.	Resistance of coil.	Temperature.
					° C.
				3·01	728
0·075	229	13·44	847		
0·075	155	13·44	573		
0·3	89	103·44	2528		
0·075	154	13·43	570		
0·3	96	103·43	2726		
1·2	132	103·43	3749		
7·3	156	103·43	4430		
37·2	181	103·43	5155		
				3·0	725

The sample was again heated until it became non-magnetic. A magnetising force of 0·075 was applied by a current in the primary during heating, and was taken off entirely by breaking the primary circuit when the sample was non-magnetic. The sample was allowed to cool to the ordinary temperature of the room, 12° C., and the following series of observations was made, the first reversal being from the direction of the force of 0·075 which had been applied when the ring was heated.

TABLE 19.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.
0·075	120	1·244	41
,,	87	,,	30
0·15	249	,,	85
,,	210	,,	72
0·3	62	11·244	193
,,	58	,,	179
0·6	178	,,	550
,,	154	,,	476
1·2	59	101·244	1,590
,,	55	,,	
2·2	227	,,	6,300
,,	223	,,	
4·0	357	,,	10,080
,,	363	,,	
7·3	226	201·24	12,553
,,	228	,,	
12·1	252	,,	13,991
,,	254	,,	
18·8	268	,,	14,876
,,	270	,,	
25·9	275	,,	15,318
,,	278	,,	
42·4	293	,,	16,148
,,	291	,,	

In addition to the fact that the first kick is largest for small forces, this shows, I think, that heating a sample above the critical temperature does not destroy its remembrance of magnetic force applied before and during heating. It would seem that the molecules of iron lie as they were placed by the magnetising force even after their magnetisation has disappeared by heating, and that when they become again capable of magnetisation by cooling the effect of the position of their axes is again apparent.

The ring was now demagnetised by reversed currents, but these were successively reduced to a force of 0·0075, instead of 0·05 as heretofore, and the following series of observations was made :—

TABLE 20.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.
0·075	77·0	1·24	27
„	79·0		
0·15	180·0	„	62
„	183·0		
0·3	52·0	11·24	161
„	52·5		
0·6	126·0	„	389
„	125·0		
1·2	47·5	101·24	1,314
„	47·0		
2·1	222·0	„	6,172
„	223·0		
4·0	361·0	„	10,119
„	366·0		
7·5	228·0	201·24	12,636
„	228·0		
12·3	253·0	„	13,991
„	252·0		
18·8	270·0	„	14,903
„	269·0		
25·1	276·5	„	15,277
„	276·0		
42·2	291·0	„	16,037
„	289·5		

This series shows two things : first, when the demagnetising force is taken low enough there is no asymmetry in the galvanometer kicks ; second, the effect of demagnetising by reverse currents is to reduce the amount of induction for low forces.

The ring was now heated to a resistance of secondary of 3·18, temperature 783° C., the ring becoming non-magnetic at 3·03, temperature 734° C. or thereabouts, a magnetising force of about 12 C.G.S. units being constantly applied. The magnetising force was then taken off and the ring was allowed to cool, and the following series was made ; the first kick being in all cases produced by reversal from the direction of the current applied during heating.

TABLE 21.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.
0·15	28·5	11·26	87
,,	28·0		
,,	218·0	1·26	75
,,	214·0		
0·3	66·5	11·26	205
,,	66·0		
0·6	182·0	,,	565
,,	167·0	,,	518
,,	162·0	,,	502
,,	157·0	,,	488
1·2	329·0	21·26	1,925
,,	293·0	,,	1,714
2·2	230·0	101·26	6,398
,,	227·0		
4·0	181·0	201·26	10,000
,,	179·0		
7·3	225·0	,,	12,410
,,	223·0		
11·6	250·0	,,	13,850
,,	249·0		
18·0	264·0	,,	14,626
,,	263·0		
28·3	274·0	,,	15,180
,,	274·0		
46·2	288·0	,,	15,900
,,	286·0		

From this table it will be observed that the induction for low forces has again increased; that the ring still recollects its state previous to heating.

The ring was again demagnetised, with currents ranging down to 0·0075, and the following series of experiments was made :—

TABLE 22.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.
0·075	74·5	1·26	26
,,	76·5		
0·15	175·0	,,	62
,,	180·0		
0·3	51·5	11·26	161
,,	52·5		
0·6	125·0	,,	389
,,	125·0		
1·2	231·0	21·26	1,331
,,	224·0		
2·2	223·0	101·26	6,272
,,	224·0		
4·0	361·0	,,	10,192
,,	365·0		
7·7	224·0	201·26	12,576
,,	229·0		
13·1	252·0	,,	14,016
,,	254·0		
20·4	266·0	,,	14,847
,,	269·0		
28·8	277·0	,,	15,346
,,	276·0		
51·7	292·0	,,	16,455
,,	292·0		

It will be seen that this series agrees very closely with Table 20, evidence of the general accuracy of the results.

The ring was lastly demagnetised and heated to a resistance of secondary of 3·19, temperature 787° C., under a magnetising force ·075, which was removed when the ring was at its highest temperature; the ring was cooled, and the following observations made. In this case, however, the first kick was due to a reversal from a current opposed to the current which was applied during heating.

TABLE 23.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.
0·075	84·0	1·43	33
,,	84·5		
0·15	192·0	1·43	75
,,	195·0		
0·3	60·0	11·43	192
,,	62·0		
0·6	153·0	,,	480
,,	154·0		
1·2	321·0	21·43	1,891
,,	? 302·5		
2·2	239·0	101·43	6,678
,,	238·0		
4·0	367·0	,,	10,262
,,	366·0		
7·3	227·0	201·43	12,576
,,	226·0		

This shows doubtfully the effects of magnetisation previous to heating, but, comparing it with Table 10, it completes the proof that the asymmetry was in that case due to the magnetising force, which had been stopped when the ring was non-magnetic.

I have dwelt at length on these experiments because they show two things: first, that heating until the ring becomes non-magnetic does not clear the material of the magnetism when it is afterwards cooled; second, that demagnetisation by reversal does not bring back the material to its virgin state, but leaves it in a state in which the induction is much less for small forces and greater for medium forces than a perfectly demagnetised ring would show.

To return to the effects of temperature, Curves XX., XXI., and XXII. show the relation of permeability to temperature for magnetising forces 0·3, 4, and 30.

It will be seen that they present the same general characteristics as the curves for wrought iron. The irregularities are due in part, no doubt, to the dependence of the observations on previous operations on the iron; in part, to uncertainty concerning the exact agreement of temperature of iron and temperature of secondary coil.

Whitworth's Hard Steel.—This sample was supplied to me with the following analysis of its composition:—

	C	Mn	S	Si	P
Per cent.	962	·212	·017	·164	·016

The dimensions of the ring were exactly the same as the mild steel.

The secondary coil had 56, the primary 101, convolutions.

The resistance of the secondary and leads was ·732 at 8° C.

Experiments were first made with the ring cold, partly to show the changes caused by annealing, and partly to examine the behaviour of the virgin steel.

The first series given in Table 24 was made on the virgin steel. The actual elongations on the galvanometer are given, as they afford a better idea of the probable errors of observation. These show that for very small forces the first and second elongations are practically equal, but that for forces between 1 C.G.S. unit and 14 C.G.S. units the first elongation is very materially greater than the later elongations.

The ring was now demagnetised, with magnetising forces ranging down to 0·0045, and the experiment was repeated, the results being shown in Table 25. Comparing them with Table 24, we see that the effect has been to reduce the inductions for low forces, as was the case with mild steel, and to render the kicks practically equal, whether they arise from the current first applied or subsequently applied.

The ring was not now demagnetised; the last current, giving a magnetising force 35·36, was removed, but not reversed, and a series of experiments made, the first reversal in each case being from the direction of the current of 35·36 last applied. The results are given in Table 26.

TABLES 24–26.

Table 24, Curves XXIII. and XXIV.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.
0·065	27·0 28·0	1·164	9
0·13	57·5 57·5	,,	18
0·26	116·0 117·5	,,	37
0·52	234·0 236·0	,,	75
1·04	56·5 55·5	11·164	172
2·08	123·5	,,	379
	117·5		361
	116·0 116·5	,,	356
3·74	302·0	,,	927
	276·0	,,	847
	270·0	,,	829
	262·0	,,	804
	261·5 261·5	,,	802
	258·5 257·0	,,	792
6·66	93·5 89·5	101·16	2,543
	87·0 85·0	,,	2,391
	85·5 83·5	,,	2,349
10·61	250·5 247·0	,,	6,922
	234·5 226·0	,,	6,394
	225·0 230·0	,,	6,338
15·18	168·0 171·0	201·16	9,346
	173·0 169·0	,,	9,456
20·28	190·0 197·0 194·0 193·0	,,	10,728
35·88	226·0 228·0 227·0 227·0	,,	12,553

Table 25, Curve XXV.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.
0·065	26·5 26·0	1·164	8
0·13	55·0 53·5	,,	17
0·26	106·0 106·0	,,	34
0·52	213·0 213·0	,,	68
1·04	51·5 51·5	11·164	158
2·08	108·0 105·0	,,	328
3·74	241·0 240·0	,,	740
6·66	80·0 78·0	101·164	2,196
10·82	223·0 226·0	,,	6,227
15·18	163·0 164·0	201·164	9,069
21·0	193·0 197·0	,,	10,783
35·36	226·0 226·0	,,	12,498

Table 26.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.
0·065	25·0 15·0	1·164	8
0·26	111·5	,,	36
	57·0	,,	18
	59·5	,,	19
	57·5	,,	18
3·95	311·5	11·164	956
	140·5	,,	431
	144·0 145·0	,,	445
	136·0 132·0	,,	411
	135·0 134·0	,,	414
11·44	290·0	101·16	8,062
	257·0	,,	7,145
	254·0 251·0	,,	7,033
	252·0 250·0	,,	6,950
16·43	175·0 173·0	201·16	9,622
	172·0 172·0	,,	9,512

The ring was now thoroughly demagnetised and heated till it became non-magnetic. It was then cooled slowly, and the following observations were made :—

Tables 27–33.

	Table 27.	Table 28, Curve XXVIII.	Table 29, Curve XXIX.	Table 30, Curve XXX.
Resistance at beginning of experiment	2·805	2·795	2·77	2·74
Temperature at beginning of experiment	687° C.	682° C.	674° C.	664° C.
Resistance at end of experiment	2·795	2·77	2·74	2·72
Temperature at end of experiment	682° C.	674° C.	664° C.	657° C.

Table 27. Magnetising force.	Table 27. Induction per sq. cm.	Table 28. Magnetising force.	Table 28. Induction per sq. cm.	Table 29. Magnetising force.	Table 29. Induction per sq. cm.	Table 30. Magnetising force.	Table 30. Induction per sq. cm.
0·065	9	0·065	24	0·065	45	0·065	43
0·13	21	0·13	53	0·26	197	0·26	184
0·26	61	0·26	123	1·04	873	1·04	..
		0·52	291	3·22	3578	..	1087
		1·04	821	8·32	4629	3·32	3621
		2·08	1595	18·2	5396	8·32	4771
		3·33	2215			18·51	5652
		5·51	2868				
		8·32	3301				

	Table 31, Curve XXXI.	Table 32, Curve XXXII.	Table 33, Curve XXXIII.
Resistance at beginning of experiment	2·72	2·43	2·35
Temperature at beginning of experiment	657° C.	561° C.	534° C.
Resistance at end of experiment	2·73	2·35	2·28
Temperature at end of experiment	661° C.	534° C.	511° C.

Table 31. Magnetising force.	Table 31. Induction per sq. cm.	Table 32. Magnetising force.	Table 32. Induction per sq. cm.	Table 33. Magnetising force.	Table 33. Induction per sq. cm.
0·065	42	0·065	27	0·065	24
0·26	171	0·26	112	0·26	103
1·04	1010	1·04	539	1·04	516
3·22	3706	3·22	..	2·08	1406
..	..	..	3396	3·43	3243
8·32	4885	8·53	5377	8·53	5414
19·8	5708	21·2	6707	21·53	6768

When cold, the resistance of the secondary coil and leads was 0·768 ; in calculating the temperatures, it is assumed that the cold resistance is 0·768. It is obvious that there is here considerable uncertainty concerning the actual temperatures, owing to the changes in the condition of the wire due to its oxidation.

The following series was next made, the mean results being given in

TABLE 34, Curve XXVI.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.
0·065	29	1·198	10
0·13	58	1·198	19
0·26	120	1·198	40
0·52	251	1·198	83
1·04	66	11·198	203
3·74	170	21·198	991
6·03	159	101·2	4,420
9·78	283	,,	7,867
13·94	176	201·2	9,733
15·81	187	,,	10,341
22·67	211	,,	11,668

The ring was now demagnetised, and another series of determinations was made, the mean results being given in

TABLE 35, Curve XXVII.

Magnetising force.	Galvanometer kick.	Resistance in circuit.	Induction per sq. cm.
0·065	26	1·198	9
0·13	54	,,	18
0·26	111	,,	37
0·52	236	,,	78
1·04	60	11·198	185
2·08	132	,,	407
3·74	327	,,	1,007
6·24	130	101·2	3,614
9·78	265	,,	7,367
13·10	168	201·2	9,290
15·7	187	,,	10,341
22·67	211	,,	11,668

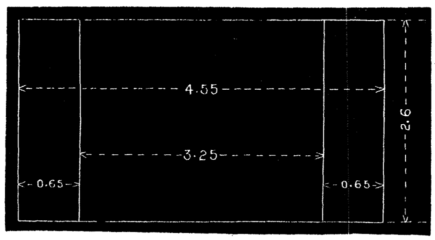
Comparing Curves XXV. and XXVII., we see the effect of annealing the iron to be to increase its permeability. Comparing Curves XXVI. and XXVII. we see the effect of demagnetising by reversed currents. Curve XXXIV. shows the relation of permeability to temperature for a force of 1·5.

Manganese Steel.—The sample of this steel was given to me by Mr. HADFIELD, who also supplied me with the following two analyses of the sample :—

	Per cent.	Per cent.
C	·74	·73
Si	·50	·55
S	·05	·06
P	·08	·09
Mn	11·15	12·06

It is well known that this steel at ordinary temperatures, and for both great and small magnetising forces, is but very slightly magnetic. The object of these experiments was to ascertain whether it became magnetic at any higher temperature.

The dimensions of the ring were as shown in the accompanying section :—



Thus the mean area of section is 1·7 sq. cm., and the mean length of lines of magnetic force 12·3 cms. The ring was wound with 52 convolutions for the secondary and 76 convolutions for the primary. It was not possible to accurately estimate the mean area of the secondary; it is, however, assumed to exceed the mean area of the steel by as much as the secondary of the sample of wrought iron is estimated to exceed the area of that sample; this gives an area of 2·38 sq. cms.

A preliminary experiment at the ordinary temperature gave induction 67·7; magnetising force 26·9.

The induction in the airspace between the wire and steel will be $26 \cdot 9 \times 0 \cdot 68 = 18 \cdot 3$; deducting this from 67·7, we obtain the induction in the steel equal to 49·4, or 29·0 per sq. cm.; dividing this by 26·9, we obtain 1·08 as the permeability from this experiment.

After the ring had been heated to a high temperature, about 800° C., and had been allowed to cool, a second experiment gave total induction 76, magnetising force 22·8, permeability 1·5.

The ring was again heated and allowed to cool, observations being made both during rise and fall of temperature, with the following results :—

TABLE 36.

Resistance of secondary and leads.	Temperature.	Total induction.	Permeability.
	° C.		
0·77	9·0 (room)	67·7	1·08
2·20	476·0	93·1	1·95
3·00	757·0	101·7	2·19
3·23	816·0	71·7	1·45
3·30	841·0	72·0	1·42
3·14	787·0	72·0	1·38
2·80	674·0	92·3	1·99
0·79	8·8 (room)	94·5	1·99

As the changes in the temperature were in this case made somewhat rapidly, the temperature of the ring lags behind the temperature of the copper.

These show: first, that at no temperature does this steel become at all strongly magnetic; second, that at a temperature of a little over 750° C. there is a substantial reduction of permeability; third, that above this temperature the substance remains slightly magnetic; fourth, that annealing somewhat increases the permeability of the material.

Resistance of Iron at High Temperatures.

These experiments were made in a perfectly simple way. Coils of very soft iron wire, pianoforte wire, manganese steel wire, and copper wire were insulated with asbestos, were bound together with copper wire so placed as to tend by its conductivity for heat to bring them to the same temperature, and were placed in an iron cylindrical box for heating in a furnace. They were heated with a slowly rising temperature, and the resistance of the wires was successively observed, and the time of each observation noted. By interpolation the resistance of any sample at any time intermediate between the actual observations could be very approximately determined. The points shown in Curves XXXV., XXXVI., XXXVII., were thus determined. In these curves the abscissæ represent the temperatures, and the ordinates the resistance of a wire having unit resistance at 0° C. Curve XXXVII. is manganese steel, which exhibits a fairly constant temperature coefficient of 0·00119; Dr. FLEMING gives 0·0012 as the temperature coefficient of this material. Curve XXXV. is soft iron; at 0° C. the coefficient is 0·0056; the coefficient gradually increases with rise of temperature to 0·019, a little below 855° C.; at 855° C. the coefficient suddenly, or at all events very rapidly, changes to 0·007. Curve XXXVI. is pianoforte wire; at 0° C. the coefficient is 0·0035; the coefficient increases with rise of temperature to 0·016, a little below 812° C.; at 812° C. the coefficient suddenly changes to 0·005. The actual values of the coefficients above the points of change must be regarded as somewhat uncertain, because the range of temperature

is small, and because the accuracy of the results may be affected by the possible oxidation of the copper. The temperatures of change of coefficient, 855° C. and 812° C., are higher than any critical temperature I had observed. It was necessary to determine the critical temperatures for magnetisation for the particular samples. A ring was formed of the respective wires, and was wound with a primary and secondary coil, and the critical temperature was determined as in the preceding magnetic experiments: it was found to be for the soft iron 880° C., for the hard pianoforte wire 838° C. These temperatures agree with the temperatures of sudden change of resistance coefficient within the limits of errors of observation.*

Some interesting observations were made on the permanent change in the resistance at ordinary temperatures caused in the wires by heating to a high temperature. In the following table are given the actual resistances of wires at the temperature of the room :—

	Before heating.	After first heating.	Second heating.	Third heating.
Soft iron	0·629	0·624	0·72	0·735
Pianoforte wire	0·851	0·794	0·79	0·74
Manganese steel . . .	1·744	1·656	1·61	1·61

In a second experiment the resistances before heating were: soft iron 0·614, pianoforte wire 0·826; after heating, soft wire 0·643, pianoforte wire 0·72.

The effects are opposite in the cases of soft iron and pianoforte wire.

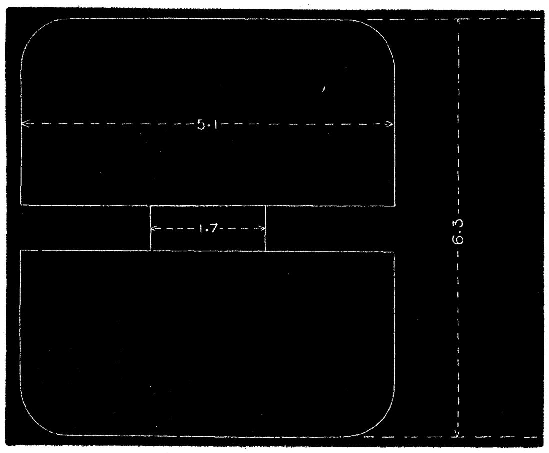
Recalescence of Iron.

Professor BARRETT has observed that, if an iron wire be heated to a bright redness and then allowed to cool, this cooling does not go on continuously, but after the wire has sunk to a very dull red it suddenly becomes brighter and then continues to cool down. He surmised that the temperature at which this occurs is the temperature at which the iron ceases to be magnetisable. In repeating Professor BARRETT'S experiments, I found no difficulty in obtaining the phenomenon with hard steel wire, but I failed to observe it in the case of soft iron wire, or in the case of manganese steel wire. Although other explanations of the phenomenon have been offered, there can never, I think, have been much doubt that it was due to the liberation of heat owing

* [*Note added July* 2, 1889.—Sir JOSEPH WHITWORTH and Co. have kindly analysed these two wires for me, with the following results:—

	C	Mn	S	Si	P
Soft iron wire	·006	·289	·015	·034	·141 per cent.
Pianoforte wire . . .	·724	·157	·010	·132	·030 „]

to some change in the material, and not due to any change in the conductivity or emissive power. This has indeed been satisfactorily proved by Mr. NEWALL.* My method of experiment was exceedingly simple. I took a cylinder of hard steel 6·3 cms. long and 5·1 cms. in diameter, cut a groove in it, and wrapped in the groove a copper wire insulated with asbestos.



The cylinder was wrapped in a large number of coverings of asbestos paper to retard its cooling; the whole was then heated to a bright redness in a gas furnace; was taken from the furnace and allowed to cool in the open air, the resistance of the copper wire being, from time to time, observed. The result is plotted in Curve XXXVIII., in which the ordinates are the logarithms of the increments of resistance above the resistance at the temperature of the room, and the abscissæ are the times. If the specific heat of the material were constant, and the rate of loss of heat were proportional to the excess of temperature, the curve would be a straight line. It will be observed that below a certain point this is very nearly the case, but that there is a remarkable wave in the curve. The temperature was observed to be falling rapidly, then to be suddenly retarded, next to increase, then again to fall. The temperature reached in the first descent was 680° C. The temperature to which the iron subsequently ascends is 712° C. The temperature at which another sample of hard steel ceased to be magnetic, determined in the same way by the resistance of a copper coil, was found to be 690° C. This shows that, within the limits of errors of observation, the temperature of recalescence is that at which the material ceases to be magnetic. This curve gives the material for determining the quantity of heat liberated. The dotted lines in the curve show the continuation of the first and second parts of the curve; the horizontal distance between these approximately represents the time during which the material was giving out heat without fall of temperature. After the bend in the curve, the temperature is falling at the rate of 0·21° C. per second. The

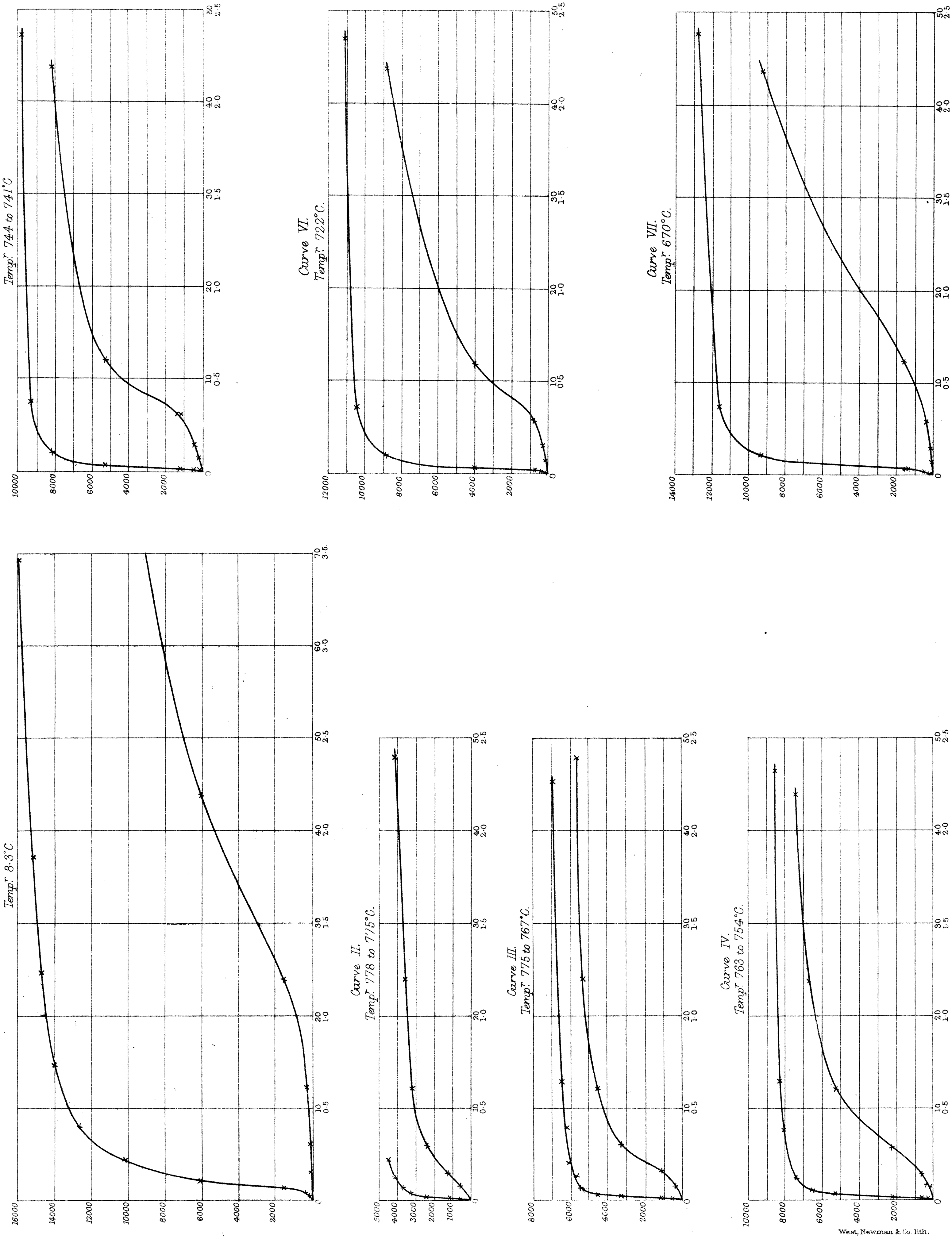
* 'Phil. Mag.,' June, 1888.

distance between the two straight parts of the curve is 810 seconds. It follows that the heat liberated in recalescence of this sample is 173 times the heat liberated when the iron falls in temperature 1° C. With the same sample, I have also observed an ascending curve of temperature. There is, in this case, no reduction of temperature at the point of recalescence, but there is a very substantial reduction in the rate at which the temperature rises.*

A similar experiment was made with a sample of wrought iron substantially the same as the wrought iron ring first experimented upon. The result is shown in Curve XXXIX. It will be seen that there is a great pause in the descent of this curve at a temperature of 820° C., but that the curve does not sensibly rise. This shows why soft iron apparently does not recalesce. Determining the heat liberated in the same way as before, we find the temperature falling after the bend in the curve at the rate of 0°·217 C. per second. The distance between the two straight parts is 960 seconds. Hence, heat liberated in recalescence is 208 times the heat liberated when the iron falls 1° C. in temperature. The temperature at which a sample ordered at the same time and place ceased to be magnetic was 780° C. Comparing this result with that for hard steel, we see that the quantity of heat liberated is substantially the same, but that in the case of the soft iron there is no material rise of temperature.†

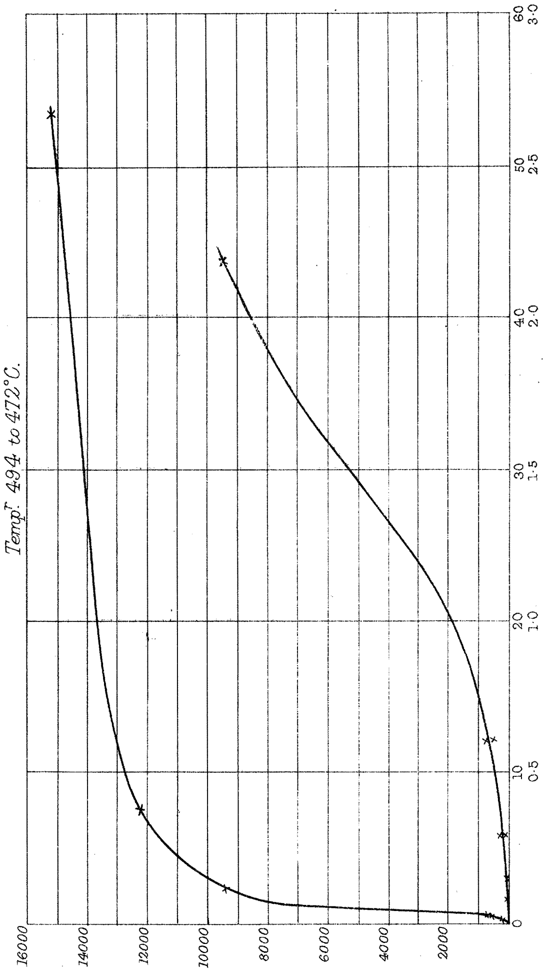
[* *Note added 2nd July*, 1889.—Some remarks of Mr. TOMLINSON'S suggested that it might be possible that there would be no recalescence if the iron were heated but little above the critical point. To test this, I repeated the experiment, heating the sample to 765° C., very little above the critical point. Curve XXXVIIIA. shows the result. From this it will be seen that the phenomenon is substantially the same whether the sample is heated to 988° C. or to 765° C.]

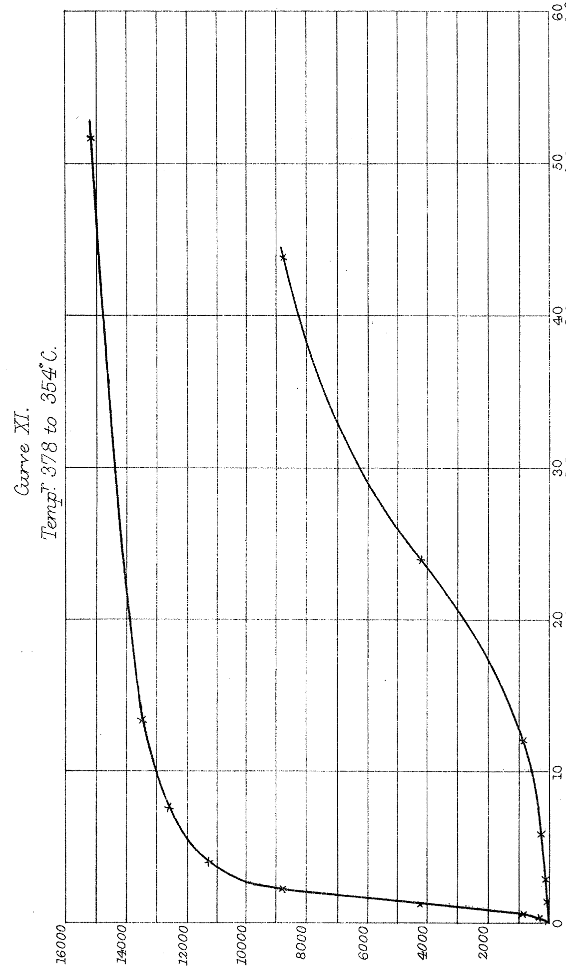
[† *Note added 2nd July*, 1889.—In order to complete the proof of the connexion of recalescence and the disappearance of magnetism, a block of manganese steel was tried in exactly the same way as the blocks of hard steel and of iron. The result is shown in Curve XL., from which it will be seen there is no more bend in the curve than would be accounted for by the presence of a small quantity of magnetic iron, such a quantity as one would expect from the magnetic results, supposing the true alloy of manganese and iron to be absolutely non-magnetic.]

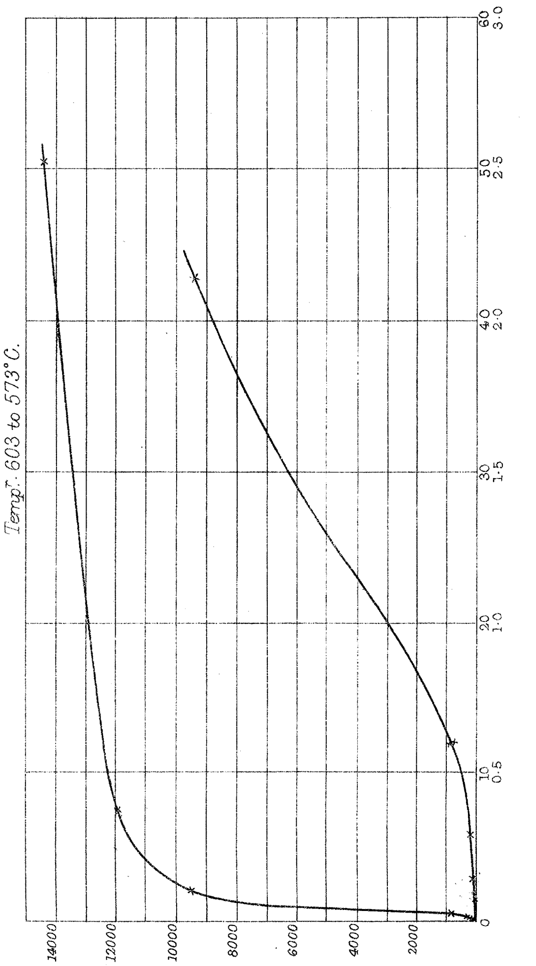


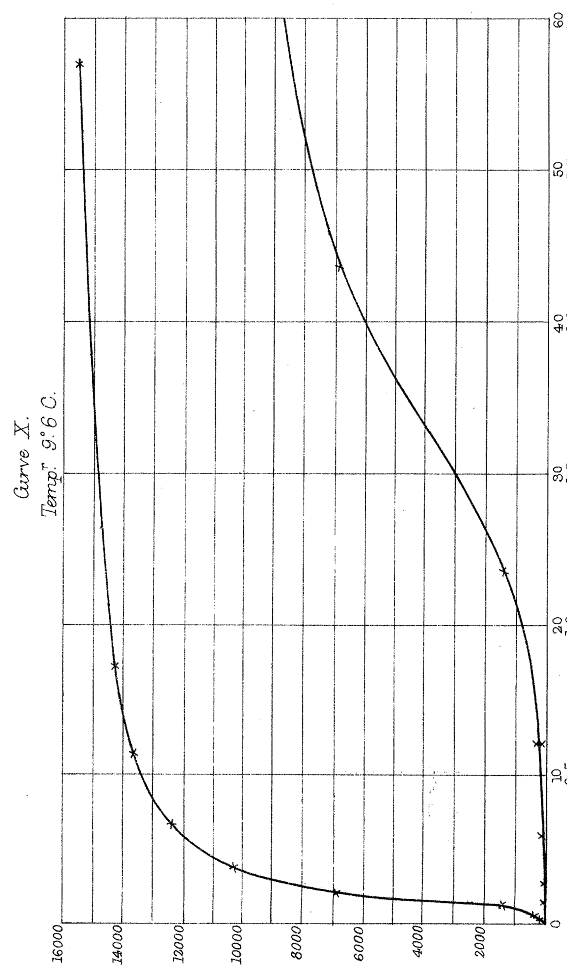
West, Newman & Co. lith.

Wrought Iron.







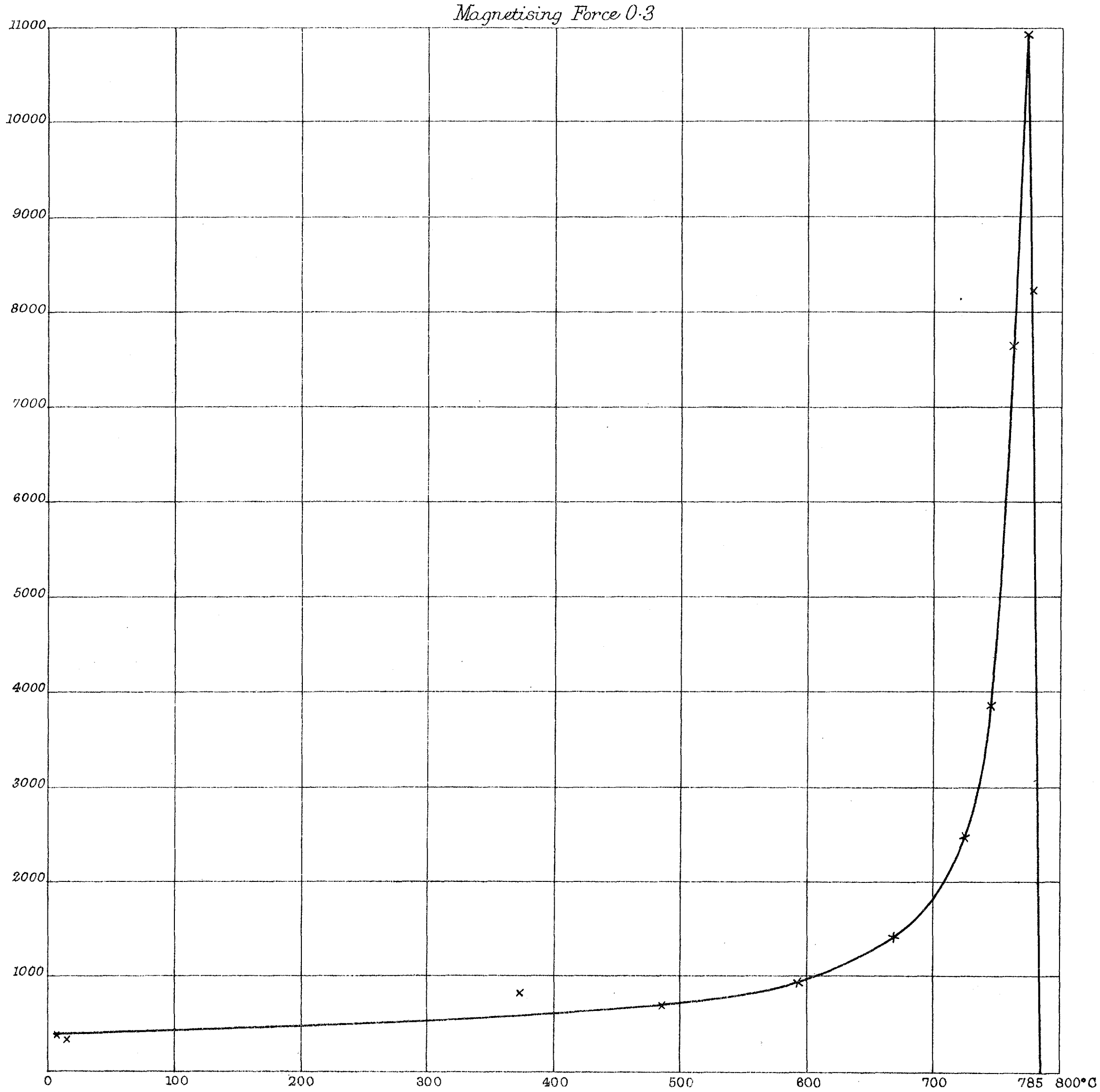


West Newman & Co. lith.

Wrought Iron.

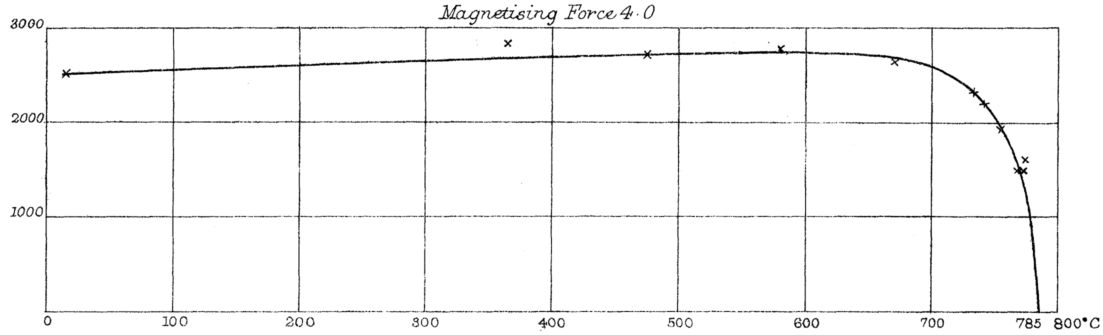
Curve XII.

Magnetising Force 0·3



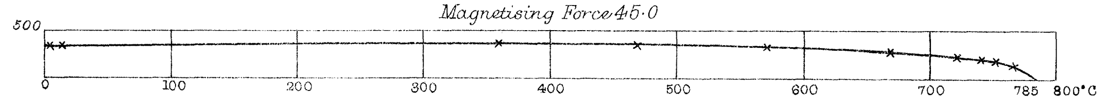
Curve XIII.

Magnetising Force 4·0



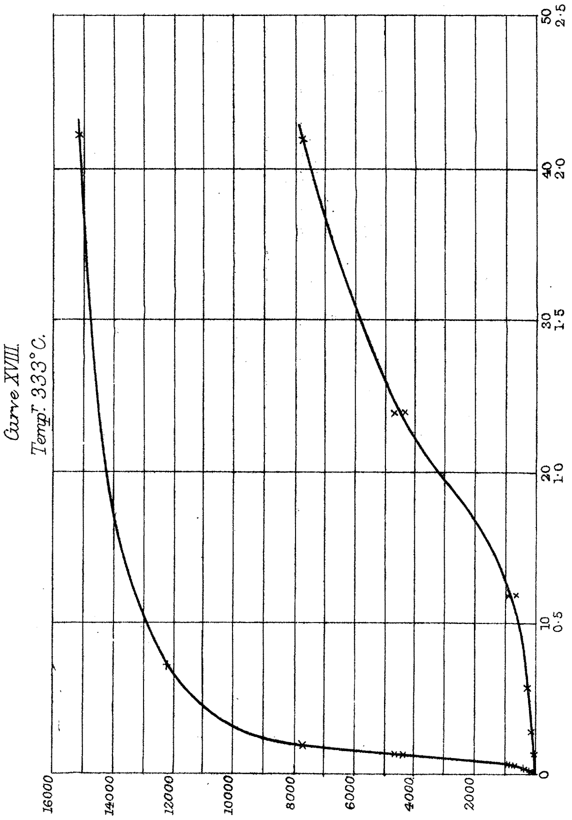
Curve XIV.

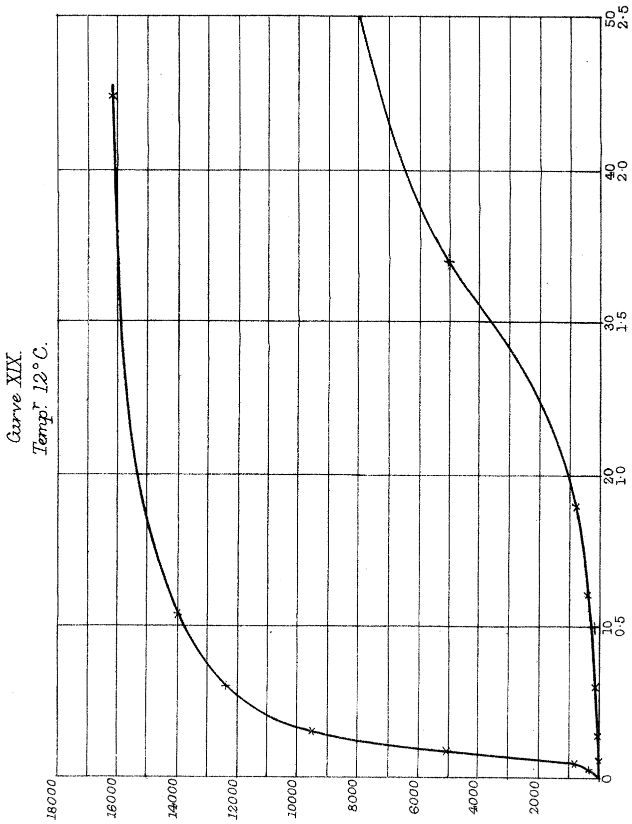
Magnetising Force 45·0

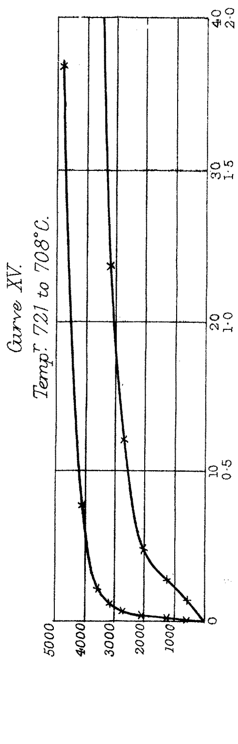


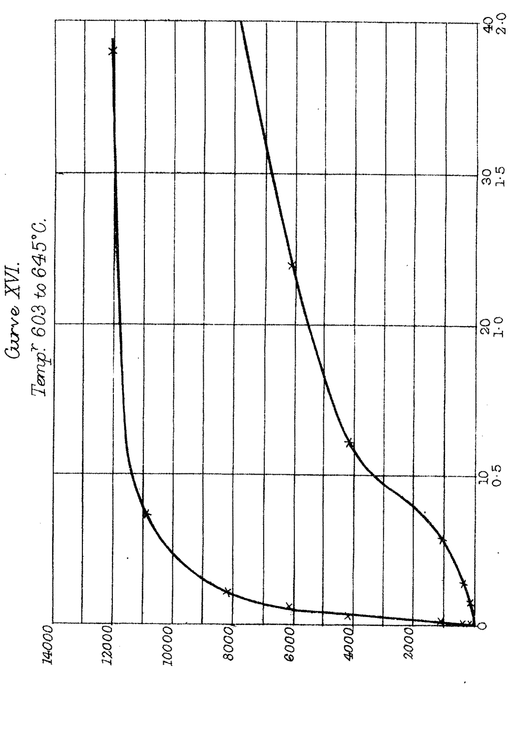
West, Newman & C° lith.

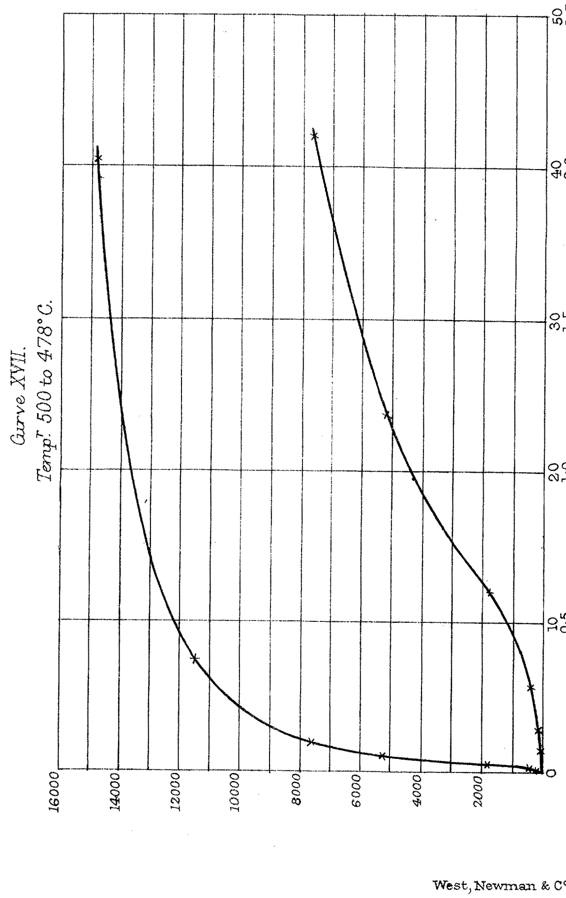
Whitworth's Mild Steel.







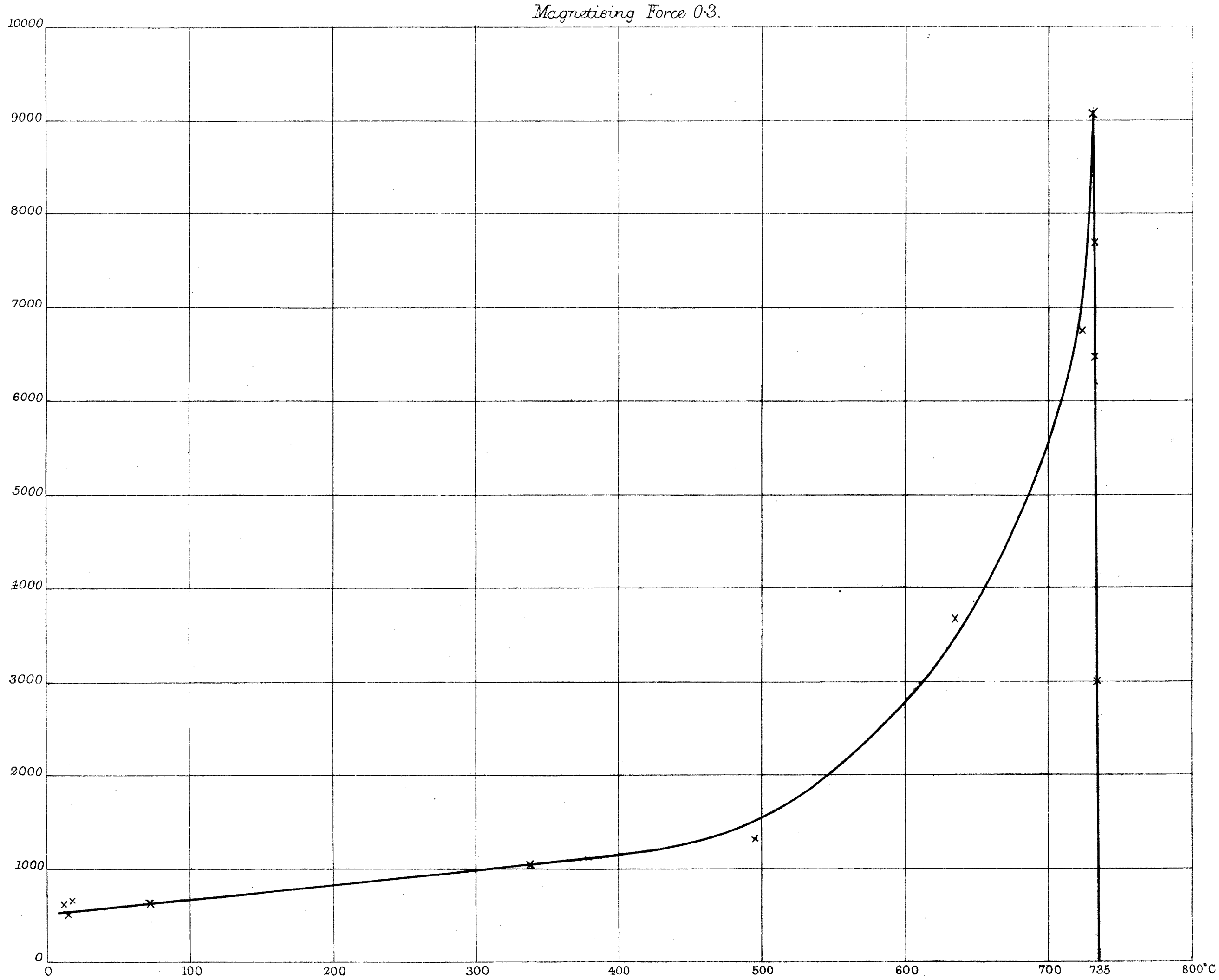




Whitworth's Mild Steel.

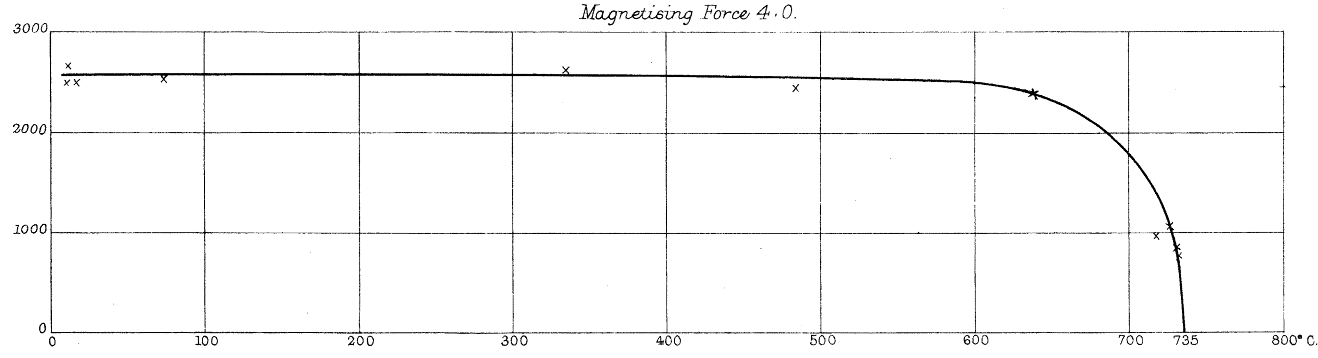
Curve XX.

Magnetising Force 0·3.



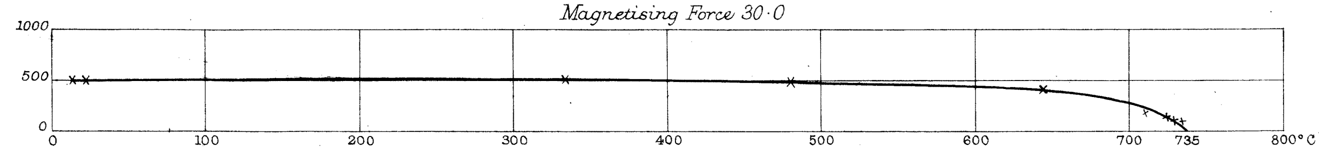
Curve XXI.

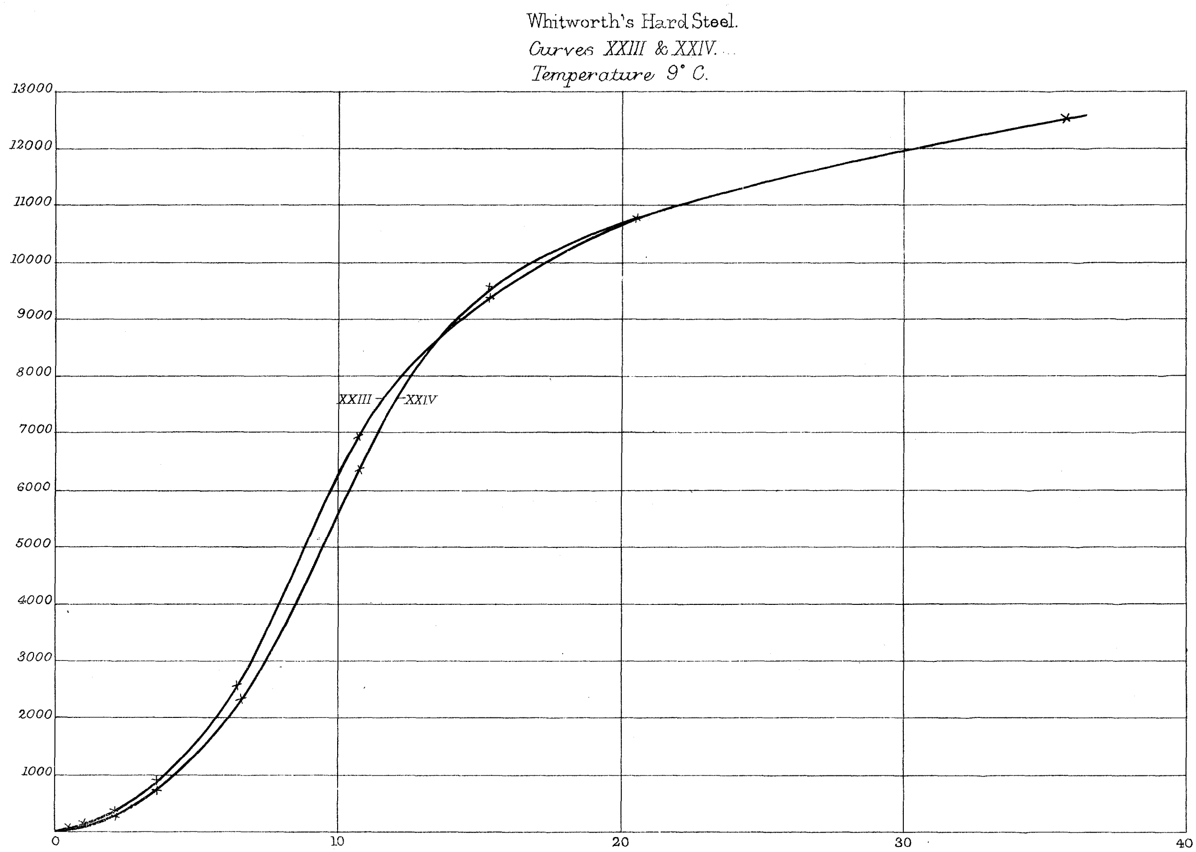
Magnetising Force 4·0.

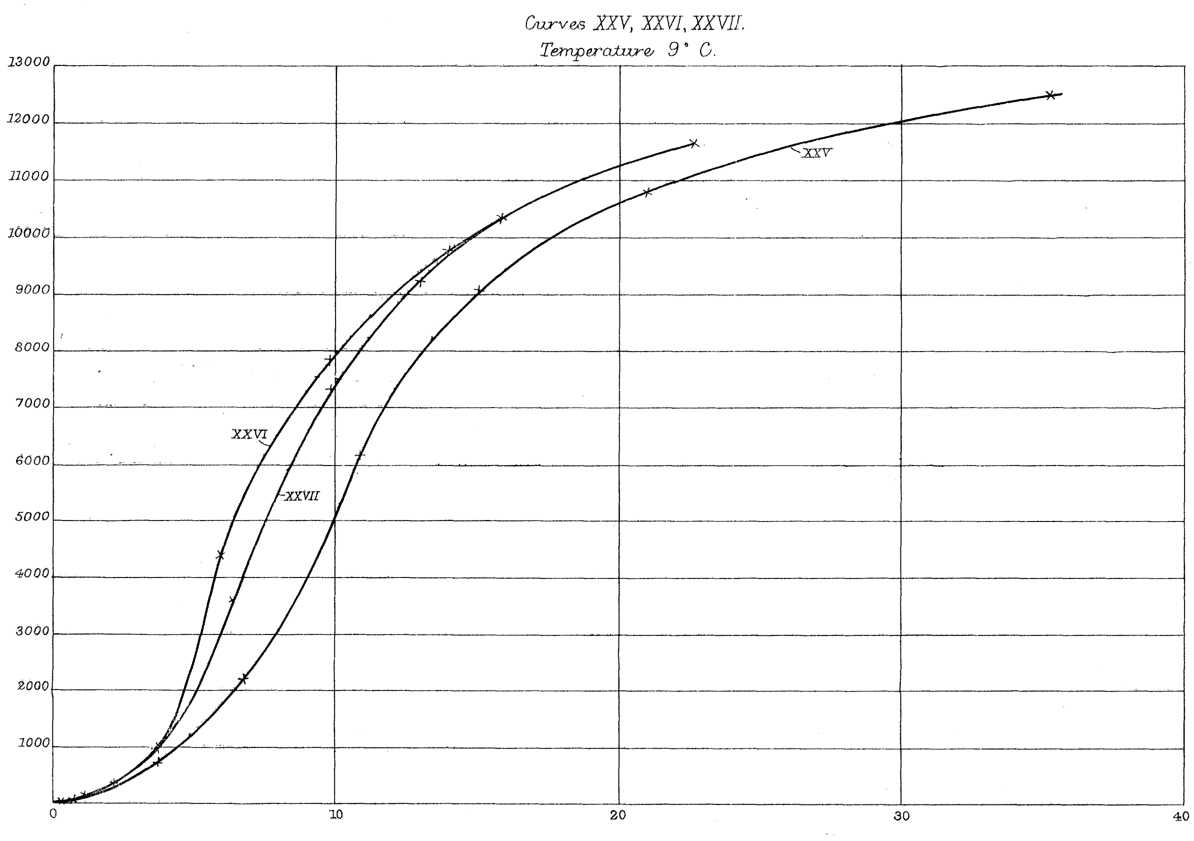


Curve XXII.

Magnetising Force 30·0



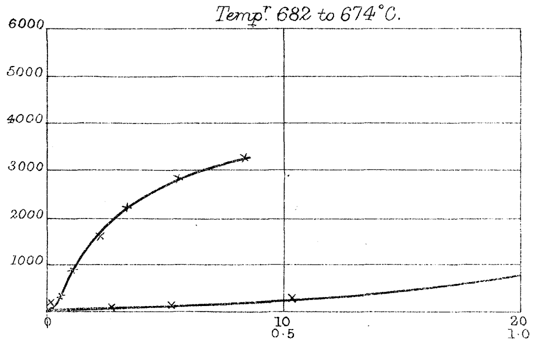




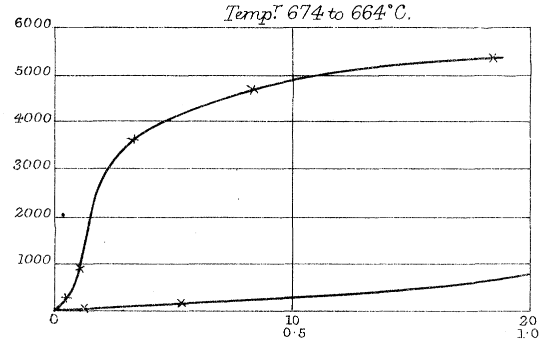
West, Newman & C° lith.

Whitworth's Hard Steel.

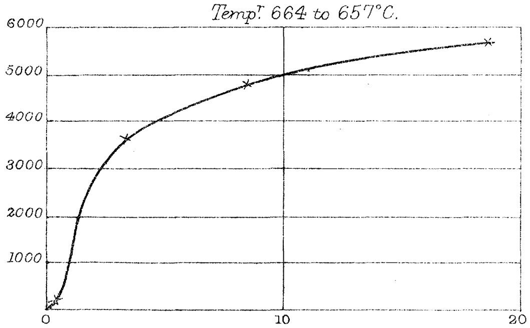
Curve XXVIII.
Tempr. 682 to 674°C.



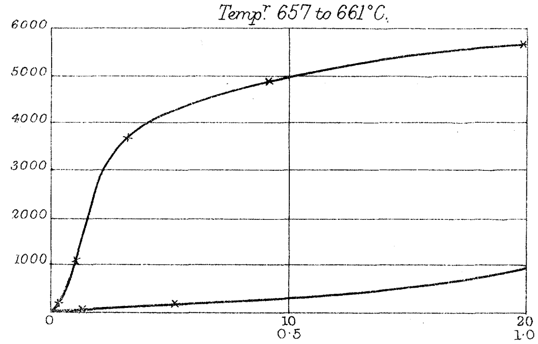
Curve XXIX.
Tempr. 674 to 664°C.



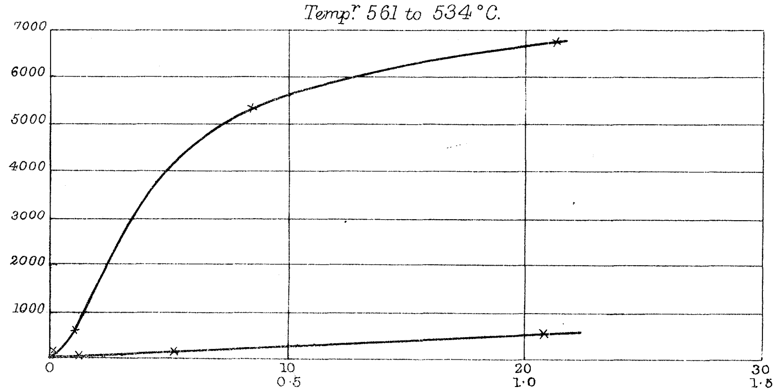
Curve XXX.
Tempr. 664 to 657°C.



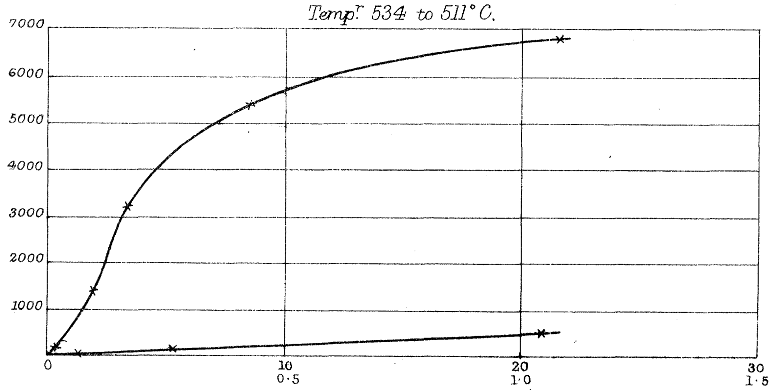
Curve XXXI.
Tempr. 657 to 661°C.



Curve XXXII.
Tempr. 561 to 534°C.



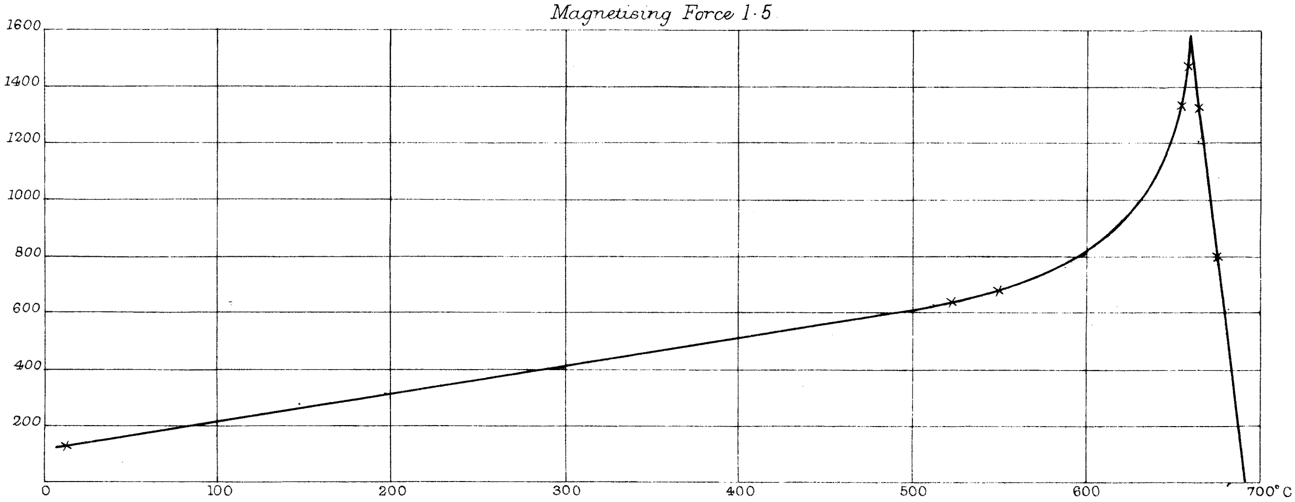
Curve XXXIII.
Tempr. 534 to 511°C.



Whitworth's Hard Steel.

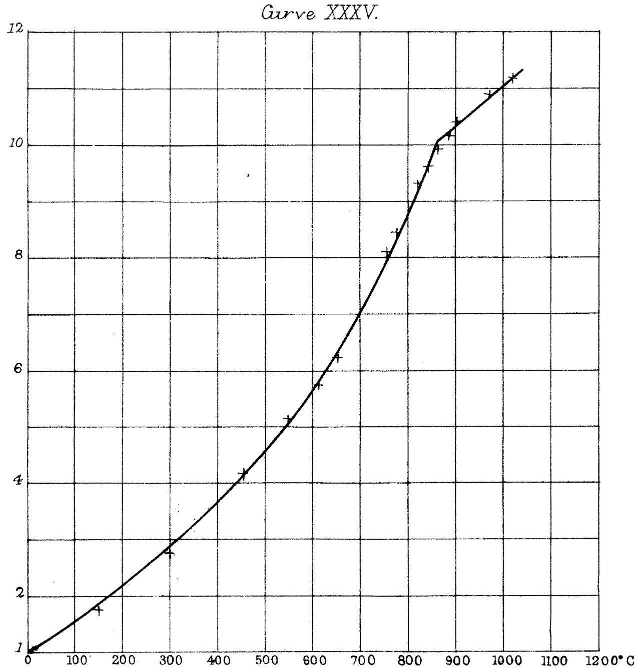
Curve XXXIV.

Magnetising Force 1·5



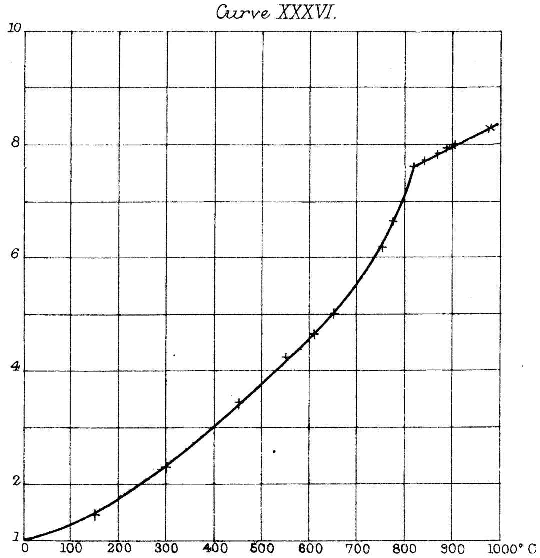
Soft Iron wire.

Curve XXXV.



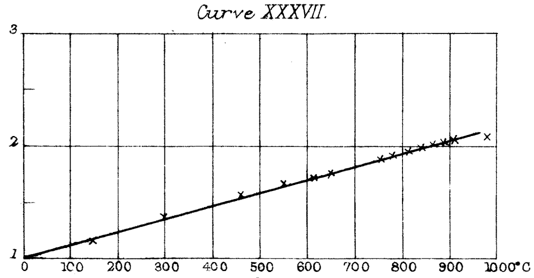
Pianoforte wire.

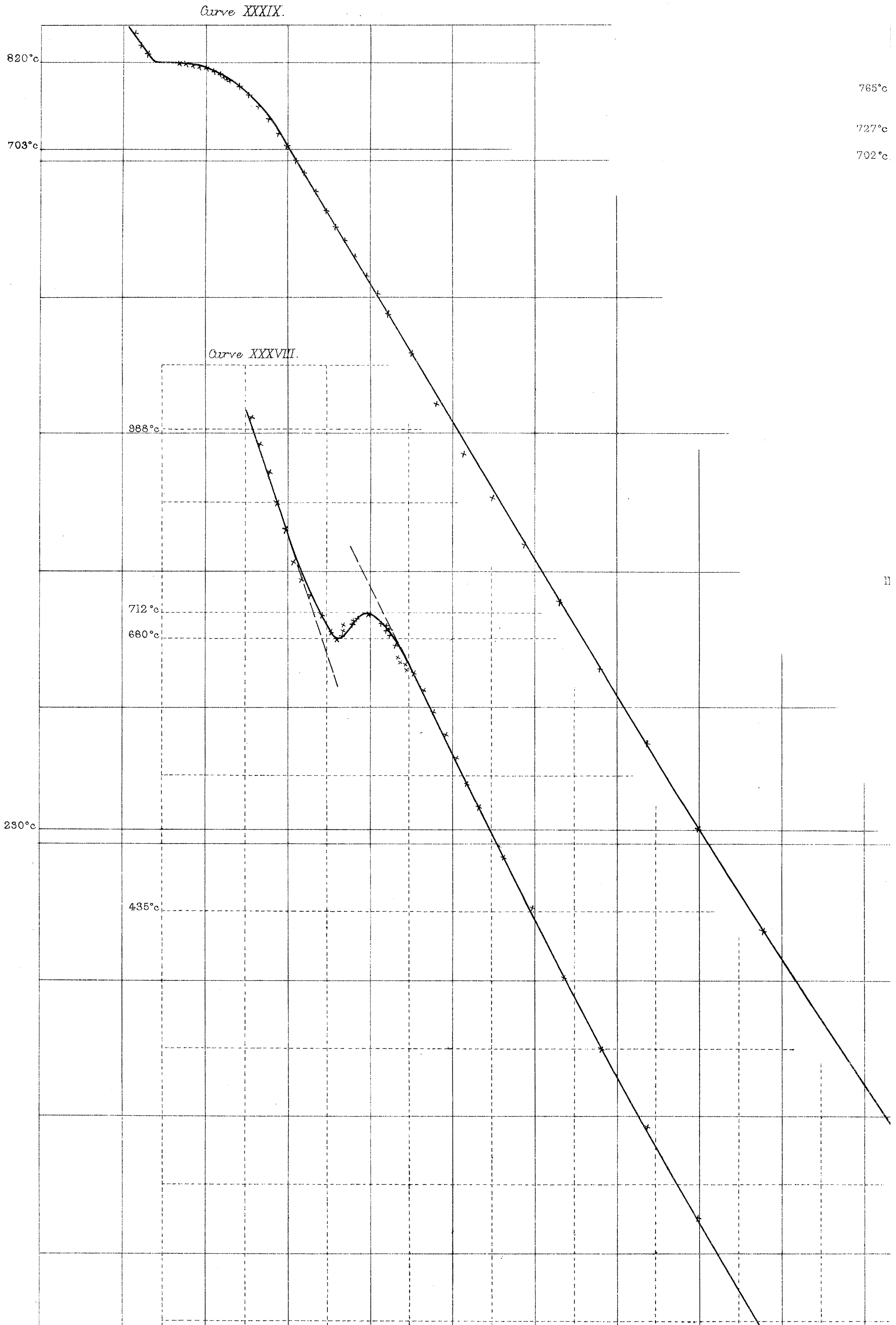
Curve XXXVI.



Manganese Steel Wire.

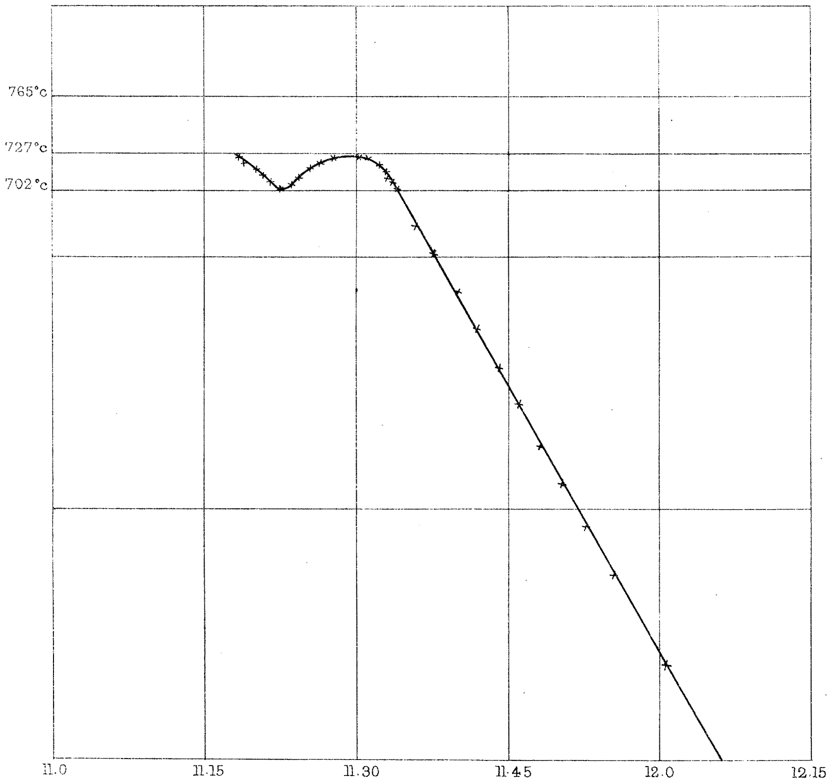
Curve XXXVII.



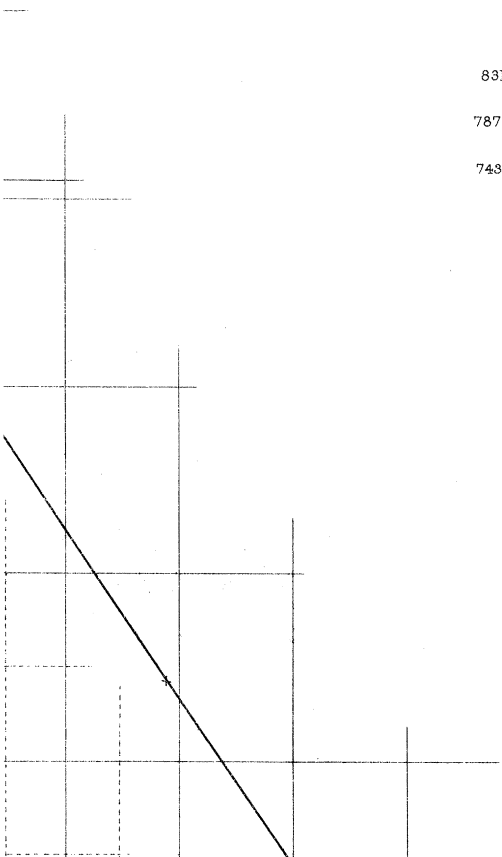


Curve XXXIX.
820°c
703°c
765°c
727°c
702°c
Curve XXXVIII.
988°c
712°c
680°c
230°c
435°c

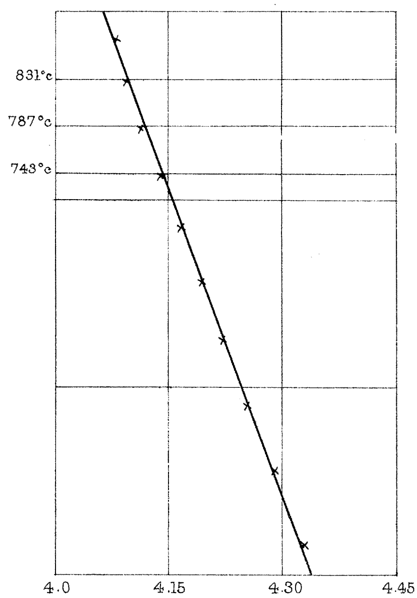
Curve XXXVIIIA.



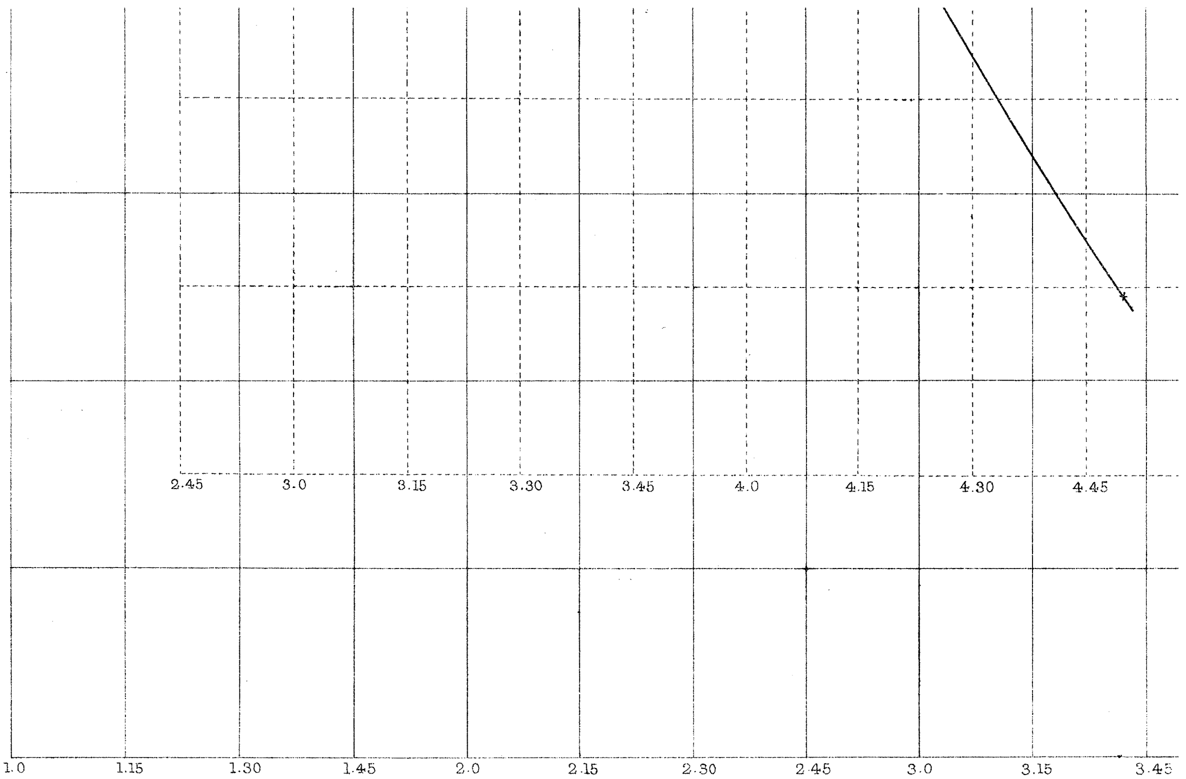
West Newman & C° lith.



Curve XL.



Hopkinson.


2.45
3.0
3.15
3.30
3.45
4.0
4.15
4.30
4.45
1.0
1.15
1.30
1.45
2.0
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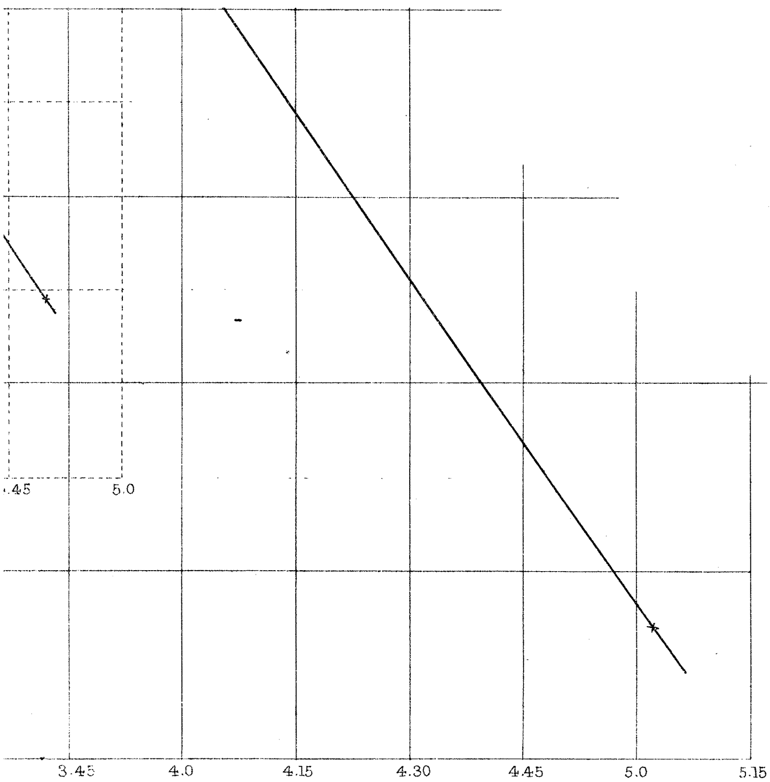
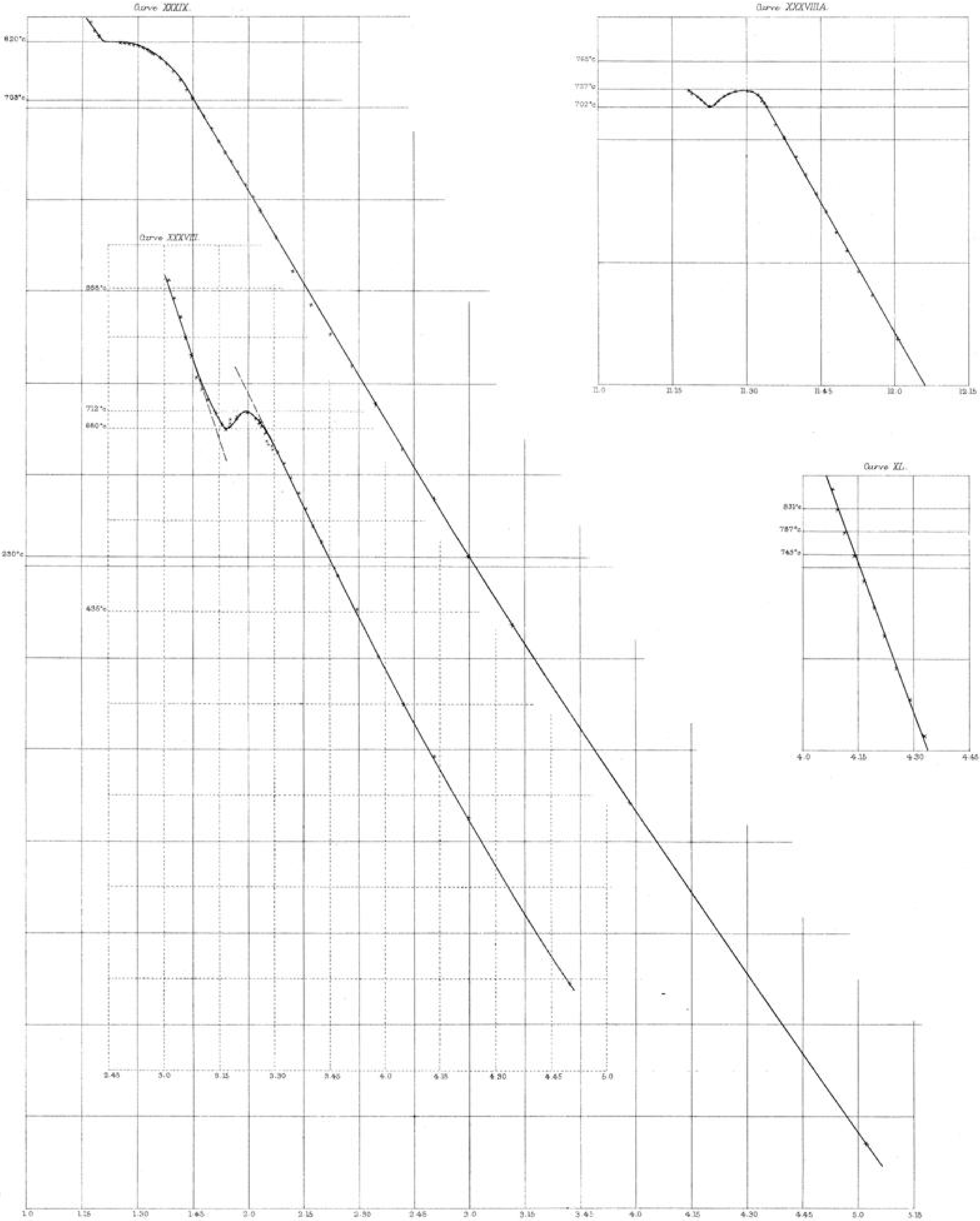
3.0
3.15
3.45



.45
5.0
3.45
4.0
4.15
4.30
4.45
5.0
5.15



West, Newman & Co lith.

Hopkinson.