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On the Magnetization and the Magnetic Change of Length in Ferromagnetic Metals and Alloys at Temperatures ranging from −186°C to +1200°C.

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With 4 plates.

In this journal Vol. XIX., Art. 11, 1903, Professor H. NAGAOKA and one of us published the result of experiments on the magnetization and magnetostriction of nickel steels containing different percentages of nickel. The present experiment was undertaken, on the one hand, to extend the above investigation to different temperatures, and on the other hand, to form a continuation of our former experiment.*

The experiment was made in three separate stages. In the first experiment, which extended from February 21 to July 2, 1903, the magnetization and the magnetic change of length at ordinary and liquid air temperatures were measured; in the second experiment extending from January 17 to February 2,

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*) K. HONDA and S. SHIMIZU, this Jour. Vol. XIX, Art. 10, 1903.

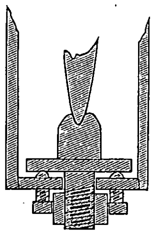
1904, the same measurements were extended so as to include different intermediate temperatures between the ordinary and liquid air temperatures; lastly in the third experiment, which extended from March 10 to May 17, 1904, the magnetizations at high temperatures were measured.

Our specimens consisted of five ferromagnetic metals, and twelve specimens of nickel steels, kindly placed at our disposal by M. Ch. Ed. GUILLAUME. They were all examined in the form of ovoids (major axis = 20 cm and minor axis = 1 cm).

In the first experiment, the specimens were first annealed for about 4 hours at 1000°C–1100°C in charcoal fire, after they were well wrapped in asbestos, and then gradually cooled. These annealed specimens were tested at the ordinary, then at liquid air temperature, and lastly again at ordinary temperature. In the second experiment, the measurement was always commenced with freshly annealed ovoids. Lastly in the third experiment, all specimens were cooled in liquid air for about 15 or 20 minutes. The measurements at the ordinary, and then at higher temperatures, were carried out; the measurements at different descending temperatures down to the ordinary were also made. Thus all the measurements, when set down in order, form a complete cycle with regard to temperatures, whose limits lie between liquid air temperature and 1200°C. The methods and the results of the experiments are given in the following pages.

I. FIRST EXPERIMENT.

The apparatus for measuring the change of length was similar to that used in our former experiment above referred to. The ends of the ovoid to be tested were soldered to two short brass rods, each end of the ovoids entering about 2 mm into the rod. The upper piece is connected with a wire stretched vertically, and the lower piece is screwed to the bottom of the specimen-holder, as shown in the annexed cut. The axis of the ovoid can be adjusted by three small screws. The holder was made of a copper tube, with three long slits, equally distant from one another, along its axis. These slits permit the adjustment of the specimens to the axial line of the tube. The rest of our apparatus was exactly the same as in the former experiment.



In the present experiment, the magnetization was, at the same time, measured by the magnetometric method. The magnetometer consisted of a bell-shaped magnet suspended by a quartz fibre in a thick copper case. A magnetizing coil (length $=40$ cm, $4\pi n=394.4$) and a compensating coil of nearly the same dimensions were placed respectively due magnetic east and west of the magnetometer. The magnetometer was placed in such a position that the specimen exerted the maximum effect upon it. The vertical component of the earth's field was compensated for. The deflection of the magnetometer was measured by means of a scale and telescope.

In measuring magnetization, the following precautions were taken. The verticality of the two coils was tested by means of a level. The line of the magnetometer, the compensating coil and the magnetizing coil, was then tested by a compass needle. The compensation of the earth field and then that of the magnetizing coil were next effected; lastly the scale and telescope were placed in correct positions.

The precautions above enumerated were especially necessary, as the magnetization and the magnetic hysteresis in strong fields were to be studied with the ovoids placed in vertical positions. Though these precautions were taken with the utmost care, the magnetizations by opposite currents of equal strength were not exactly equal in absolute amounts, so that a small asymmetry of the hysteresis curve was also observed in the strong fields. This difference was, in the most unfavorable case, not greater than 1% of the total magnetization for a field of 700 C.G.S. This probably arose from a slight deviation of the coils from the vertical line. If the lines of force at the center of the magnetometer be not vertical, but be in the meridian plane, the field due to the coils may slightly affect the horizontal component of the earth's field, without producing any deflection of the magnetometer. If the horizontal component be increased by a current in one direction, a current in the opposite direction will diminish it. In the first experiment, therefore, two magnetizing curves for opposite currents were taken. These two curves almost coincided with each other below a field of 200 C.G.S., but slightly deviated above that field. Since the disturbing force is proportional to the magnetizing current, the correction for the intensity of magnetization can be derived from a pair of the opposite magnetizations by equal and opposite currents; hence in the second and third experiments, the magnetizations by equal and opposite currents of the maximum strength were taken, and the correction was found, and applied to magnetization by currents of one direction.

The current was measured by a SIEMEN-HALSKE ammeter, which was occasionally compared with a KELVIN ampere-balance.

The experiment was conducted in the following order. The adjustment of the magnetizing and compensating coils having been completed, the specimen-holder containing the ovoid was fixed vertically in the correct position in the magnetizing coil. The ovoid was then vertically stretched upwards by means of a copper wire with a spiral spring, special care being taken to stretch the copper wire in the direction of the axis of the ovoid. The magnetic change of length was then measured in the usual way. The magnetization and the magnetic hysteresis were next observed. Liquid air was next gently poured into the DEWAR tube in the magnetizing coil, until the tube was nearly filled with the liquid; then the exposed parts above the magnetizing coil were carefully protected with cotton wool. Owing to the boiling of the liquid, a small oscillation of the image in the field of the telescope was at first observed; but after some ten minutes, the image became almost steady. The change of length was then taken. Next, adding more liquid air to that in the DEWAR tube, when necessary, the magnetization and the magnetic hysteresis were measured. Lastly when the specimen was heated to the temperature of the room, the change of length and the magnetization were again noted. After the experiments, the compensation of the magnetizing current was always tested, and found perfect, except in a few cases.

(*a*) Magnetization of Ferromagnetic Metals.

In Table I, the magnetization in different fields is given, where I is the intensity of magnetization, and H the internal field (external field – demagnetizing force). The temperature of liquid air has been assumed to be −186°C; but owing to the fractional evaporation of nitrogen, as the experiment proceeds, the actual temperature may, according to circumstances, be greater or less by few degrees than the above value. The figures of the last row in each column are the residual magnetism, when the external field vanishes.

TABLE I.

SWEDISH IRON.

t=27.5°C		*t*=−186°C		*t*=21.5°C	
H	I	H	I	H	I
1.77	81	2.23	77	1.76	86
3.55	243	3.39	247	2.85	250
4.10	582	4.55	453	3.39	431
7.40	890	5.00	578	4.41	632
16.3	1138	15.4	1085	7.00	858
30.3	1251	44.7	1302	14.1	1102
53.4	1330	135.0	1464	33.7	1264
103.7	1419	221.8	1543	108.8	1424
234.6	1545	283.9	1587	225.4	1536
349	1609	385	1636	390	1623
473	1647	478	1665	485	1648
554	1621	543	1681	547	1660
	33.5		39.7		37.6

TUNGSTEN STEEL.

t=23.5°C		*t*=−186°C		*t*=30.7°C	
H	I	H	I	H	I
2.22	22	1.37	13	2.16	21
8.36	119	5.89	64	4.38	49
10.90	275	19.75	130	6.91	104
12.10	528	12.40	254	9.25	193
15.7	695	16.8	661	10.35	376
20.1	928	28.8	1035	25.8	1064
28.5	1062	62.7	1235	111.2	1326
96.6	1292	140.1	1371	216.2	1413
185.1	1381	272.4	1468	333	1463
282.1	1432	402	1523	397	1483
416	1477	469	1535	483	1499
574	1503	570	1557	557	1509
	123		136		127

NICKEL.

$t=13.0$°C		$t=-186$°C		$t=17.0$°C	
H	I	H	I	H	I
1.11	14	1.42	9	0.53	7
3.26	88	3.34	26	3.63	91
6.96	177	11.35	187	7.92	192
11.12	237	21.95	298	18.60	309
19.85	322	34.1	357	38.1	400
37.94	394	80.4	418	63.8	439
64.1	438	152.8	443	117.3	469
153.6	478	240.3	462	182.5	483
247.6	490	342	477	332	494
359	496	493	490	484	503
493	503	586	506	639	505
710	510	704	518	703	506

CAST COBALT.

$t=20.0$°C		$t=-186$°C		$t=19.5$°C	
H	I	H	I	H	I
5.1	72	3.90	28	2.58	22
10.7	170	10.57	122	14.14	223
13.9	247	22.65	277	20.03	302
22.8	371	39.3	427	24.85	374
35.7	497	74.7	608	33.1	454
54.5	628	101.9	690	50.6	594
85.9	749	206.6	848	77.3	676
147.7	865	281.1	911	121.3	780
244.3	953	357	956	275.3	941
392	1027	449	999	406	1010
467	1047	570	1038	543	1053
610	1088	668	1063	659	1083

ANNEALED COBALT.

t=18.6°C		t=−186°C		t=31.0°C	
H	I	H	I	H	I
4.37	6	7.80	9	6.94	8
13.53	26	16.23	20	18.39	29
25.25	67	39.0	64	29.23	56
36.59	115	57.8	102	45.07	108
52.5	171	80.0	148	65.0	164
86.7	257	119.6	221	95.7	232
122.3	320	167.4	282	147.5	313
221.8	433	248.4	358	167.3	415
354	532	347	426	364	508
445	583	496	504	484	572
527	613	561	543	542	603
699	687	702	589	684	664

From these numbers, we see that in Swedish iron, tungsten steel and nickel, the cooling by liquid air diminishes the magnetization in low fields, but increases it in the strong. In Swedish iron and tungsten steel, the change is very small, amounting at most to 2 or 3 per cent; but in nickel, the initial diminution is considerably larger, amounting to about 10 per cent in the maximum. The field, in which the effect of cooling changes its sign, is 115 C.G.S. for Swedish iron and tungsten steel, and 580 C.G.S. for nickel. Fleming and Dewar[*] who first thoroughly studied the magnetization of iron and steel in liquid air, did not observe an increase of magnetization; perhaps the field was too weak to indicate such an increase.

In cast and annealed cobalts, cooling always diminishes magnetization; the effect is rather greater in cobalt when annealed than in the cast state.

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*) Fleming and Dewar, Pro. Roy. Soc., **60**, 81, 1896.

In Swedish iron, tungsten steel and nickel, the magnetizations before and after the cooling coincide with each other for all fields. In cast and annealed cobalts, there is a considerable residual change of the magnetic condition.

(*b*) Magnetization of Nickel Steels.

The intensities of magnetization at the temperatures of the room and of liquid air are given in Table II.

TABLE II.

NICKEL STEEL 70.32%.

$t=21.1$°C		$t=-186$°C		$t=30.5$°C	
H	I	H	I	H	I
0.24	9	0.28	6	0.93	35
1.52	120	2.02	96	1.52	127
2.20	310	2.61	221	1.65	233
3.91	500	3.62	455	2.75	374
11.20	721	10.94	662	6.07	593
17.20	794	20.5	835	11.17	712
32.5	903	31.4	911	16.20	784
63.3	969	45.5	971	36.9	869
91.4	988	81.4	1031	52.9	952
232.1	1004	169.3	1063	101.3	987
381	1008	253.3	1072	186.0	996
492	1008	337	1078	283.6	999
576	1008	439	1088	438	999
672	1009	601	1098	628	999
	22.2				

NICKEL STEEL 50.72%.

$t=24.0$°C		$t=-186$°C		$t=32.0$°C	
H	I	H	I	H	I
1.86	58	1.22	33	1.54	55
2.92	207	3.80	197	2.24	112
3.35	324	4.13	333	2.74	191
5.16	569	5.55	509	4.44	498
8.80	727	8.27	712	8.77	736
17.12	946	21.9	1003	19.52	961
36.4	1076	27.2	1051	33.4	1066
51.4	1137	41.6	1133	49.5	1126
73.0	1181	65.8	1207	84.8	1184
146.3	1225	148.0	1285	168.0	1220
251.4	1241	230.6	1302	255.3	1229
328	1244	315	1308	375	1230
426	1246	439	1310	518	1235
604	1247	573	1312	602	1237

NICKEL STEEL 46%.

$t=20.0$°C		$t=-186$°C		$t=21.0$°C	
H	I	H	I	H	I
0.29	7	1.59	38	1.54	47
2.30	79	6.00	359	2.79	116
3.02	175	7.90	554	3.74	228
4.08	279	10.85	770	5.55	490
4.92	362	19.90	974	10.49	754
5.88	473	26.60	1059	15.30	883
8.22	684	39.6	1147	29.8	1029
11.10	793	49.0	1187	66.5	1145
17.15	909	72.8	1246	166.4	1206
33.8	1054	100.9	1295	311	1219
91.1	1171	166.6	1338	411	1221
266.7	1214	242.5	1360	489	1222
372.1	1219	455	1377	608	1222
532.9	1222	631	1384		

NICKEL STEEL 36%.

$t=13.0$°C		$t=-186$°C		$t=19.0$°C	
H	I	H	I	H	I
1.27	32	2.18	30	1.48	36
2.45	73	6.00	207	3.39	138
4.00	176	8.16	426	5.37	335
7.45	472	11.70	621	9.14	550
9.50	524	16.60	801	12.60	658
11.55	624	26.3	982	16.95	741
16.05	714	52.2	1153	29.4	863
30.4	853	72.8	1210	55.9	939
65.1	953	121.5	1279	102.2	985
110.5	989	169.0	1310	187.4	1002
203.5	1007	248.3	1332	341	1014
350	1012	326	1344	436	1015
473	1013	450	1354	528	1016
662	1014	636	1367	657	1017

NICKEL STEEL 29.24%.

$t=23.0$°C		$t=-186$°C		$t=36.5$°C	
H	I	H	I	H	I
1.58	41	5.32	33	0.69	5
2.46	66	12.97	146	4.00	27
4.41	92	24.48	382	8.45	63
22.40	138	29.38	464	18.14	180
28.5	144	43.2	573	26.45	316
35.3	147	59.0	658	38.4	394
43.7	150	71.0	696	54.1	404
83.6	156	101.1	793	91.5	544
210.5	171	152.4	886	117.8	592
324	181	235.0	981	210.4	677
440	189	307.4	1030	320	740
504	193	403.1	1080	465	789
592	197	519	1121	551	808
657	201	591	1135	623	887
			192		171

NICKEL STEEL 29%.

$t=12.0°C$		$t=-186°C$		$t=16.0°C$	
H	I	H	I	H	I
1.00	11	2.24	9	2.20	8
2.95	131	10.13	93	4.52	29
7.60	207	13.39	155	9.35	75
19.6	272	20.74	321	12.92	123
67.1	307	29.5	505	15.95	180
143.7	315	37.6	608	24.72	355
243.6	321	48.0	708	44.2	582
400	328	75.0	858	74.5	708
515	333	139.6	1036	105.7	779
532	333	182.9	1104	174.9	874
738	341	356	1247	279.3	954
		424	1276	378	1004
		517	1306	547	1052
		631	1330	664	1079

NICKEL STEEL 28.74%.

$t=22.0°C$		$t=-186°C$		$t=26.0°C$	
H	I	H	I	H	I
0.29	6	2.97	14	0.85	4
1.61	70	6.85	35	8.91	77
4.20	156	11.42	106	13.12	128
13.70	242	18.28	201	17.01	193
29.20	278	27.82	378	22.38	325
46.2	292	30.8	427	33.0	453
87.0	305	39.5	549	48.1	566
159.3	314	66.7	730	79.6	658
233.3	319	178.9	991	111.8	746
320	321	235.3	1060	207.7	851
406	327	316	1098	307	911
472	328	375	1153	457	966
627	333	461	1191	543	987
672	335	523	1227	662	1110
	17.3		226		182

NICKEL STEEL 28.32%.

$t=17.5°C$		$t=-186°C$		$t=31.7°C$	
H	I	H	I	H	I
0.52	6	3.06	23	3.77	24
2.42	23	5.21	54	6.56	51
6.40	37	9.54	107	12.34	134
14.58	48	12.43	156	21.09	262
24.24	53	23.45	375	28.10	342
43.1	59	42.7	558	44.0	452
97.2	69	86.0	759	96.0	609
206.0	84	128.8	866	188.4	726
327	98	175.9	944	264.6	799
493	112	253.4	1029	438	886
596	119	360	1104	504	904
672	126	429	1132	602	931
752	128	515	1161		
		578	1178		
	0		145		141

NICKEL STEEL 26.64%.

$t=22.0°C$		$t=-186°C$		$t=27.7°C$	
H	I	H	I	H	I
23.2	2	3.57	18	3.87	2
71.6	5	8.72	45	9.03	49
124.3	8	13.90	105	16.47	129
225.0	11	18.10	194	23.89	267
355	14	28.15	369	38.7	488
524	17	48.5	605	50.5	613
635	18	57.2	671	65.2	721
744	20	73.9	764	89.2	836
		107.6	893	145.7	982
		169.8	1023	230.0	1085
		246.0	1118	307.2	1161
		383	1219	422	1231
		466	1260	501	1255
		559	1293	621	1287

NICKEL STEEL 25%.

$t=12.5$°C		$t=-186$°C		$t=15.0$°C	
H	I	H	I	H	I
—	—	32.9	1.1	—	—
—	—	53.1	2.3	58.3	0.6
—	—	91.8	3.7	94.9	1.4
—	—	128.1	5.4	155.8	2.3
354	0.4	209.5	8.0	344.8	2.9
—	—	313	11.0	401	3.2
516	2.0	498	15.2	529	3.3
		605	17.5	749	3.3
		752	20.3		

NICKEL STEEL 24.40%.

$t=18.7$°C		$t=-186$°C		$t=23.5$°C	
H	I	H	I	H	I
29.5	1.9	6.22	23	1.03	3
71.0	3.4	12.54	60	12.22	78
126.2	5.4	28.15	241	19.16	153
230.4	7.8	40.4	359	26.2	260
412	9.3	62.7	529	37.1	408
541	10.6	93.6	675	47.6	508
653	10.8	120.0	747	63.1	630
769	11.5	183.5	860	83.7	731
		238.1	926	119.6	839
		282.8	989	174.7	933
		370.4	1034	272.8	1024
		448	1067	438	1141
		510	1107	530	1174
		575	1137	644	1210
	2.0		251		232

NICKEL STEEL 24.04%.

$t=16.0^\circ$C		$t=-186^\circ$C		$t=30.0^\circ$C	
H	I	H	I	H	I
9.5	2.6	0.99	3	3.32	11
19.6	7.2	4.35	14	8.28	36
33.8	14.1	11.14	44	16.58	101
52.8	22.2	27.35	191	29.8	295
89.8	33.2	32.9	262	54.4	575
141.3	42.4	61.3	526	67.6	657
226.6	53.1	83.4	643	83.9	741
417	68.4	107.0	725	124.3	861
536	75.6	183.8	870	169.5	942
626	79.9	260.6	968	222.8	1012
763	85.4	376	1053	322	1090
		466	1101	418	1155
		540	1143	512	1191
		591	1152	579	1212
	9.3		280		256

As in the case of iron, tungsten steel and nickel, the magnetization of the alloys of nickel steels containing percentages of nickel greater than 26.64% is decreased in weak fields and increased in strong, by cooling them in liquid air. In alloys containing lower percentages of nickel, the magnetization always increases on cooling. The amount of the change of magnetization by cooling is considerably large; with the exception of 28.73% nickel steel, it increases as the percentage of nickel decreases, up to 26.64%. The magnetization in liquid air of 25% nickel steel, which is almost non-magnetic at ordinary temperatures, is also very small. As the percentage of nickel further decreases, the change of magnetization by cooling again increases. With 26.64% nickel steel, which undergoes the greatest change of magnetization in liquid air, the intensity of magnetization increases from 16 to 1275 for H=600 C.G.S., or by about 80 times.

The magnetizations, before and after cooling, of reversible nickel steels containing greater percentages of nickel than 36%, nearly coincide with each other. If, however, irreversible nickel steels be once cooled in liquid air, the recovery to the initial value becomes less and less, as the percentage diminishes; in 24.40% and 24.04% nickel steels, the magnetization after cooling is even greater than that in liquid air. Some of the above results had already been obtained by HOPKINSON[*], OSMOND[†], and DUMAS[‡].

(*c*) Hysteresis-loss in Ferromagnetic Substances.

The hysteresis was studied at the temperature of the room and at that of liquid air. The areas of the hysteresis-loops were carefully measured by a planimeter with the results given in Table III. and in Fig. 1 a, b.

TABLE III.

FERROMAGNETIC METALS.

	Ordinary temperature.				Liquid air temperature.			
Swedish iron.	H	4.0	6.0	15.8	H	1.9	6.4	63.7
	B	4504	10660	17160	B	4792	10680	17400
	W	2236	8195	20960	W	2091	8518	23070
Tungsten steel.	H	10.7	16.8	91.5	H	12.5	18.3	91.5
	B	3493	10030	16460	B	3223	9668	16520
	W	4610	25790	56520	W	4266	28320	69750

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[*] HOPKINSON'S original papers, Vol. II, p. 227.

[†] OSMOND, C.R. CXXVIII, p. 306 and 1396, 1899; C.R. CXVIII, p. 532, 1894.

[‡] DUMAS' Recherches sur les Aciers au Nickel, p. 49—67, 1902.

	Ordinary temperature.				Liquid air temperature.			
Nickel.	H	6.3	20.9	120.5	H	1.1	26.8	122.2
	B	1996	4405	5931	B	1569	4117	5518
	W	806	3341	3915	W	1589	6763	10240
Cast cobalt.	H	6.6	12.6	92.4	H	7.4	14.8	96.3
	B	1107	2753	9259	B	960	2425	8676
	W	481	2391	21220	W	441	2272	21880
Annealed cobalt.	H	43.7	117.2	2180	H	48.3	122.7	224.3
	B	1802	3702	5508	B	1115	2893	4466
	W	5669	22680	35770	W	3244	19970	38710

Here H, B and W denote respectively the internal field, the magnetic induction, and the hysteresis-loss, all expressed in C.G.S. units. In Swedish iron, the hysteresis-loss is decreased in weak inductions and increased in the strong, by cooling it in liquid air. Fleming and Dewar* found no effect of cooling on the hysteresis-loss of iron. In tungsten steel, nickel, cast and annealed cobalts, the hysteresis-loss is always increased by cooling. These changes are briefly expressed by saying that the cooling in liquid air magnetically hardens the specimens.

In comparing the hysteresis-loss of different metals, it is to be observed that the hysteresis-loss in nickel is the smallest among them and that those for tungsten steel and cast cobalt are greater by about three times than the hysteresis-loss of Swedish iron, and the same relation also holds between annealed cobalt and tungsten steel.

From the courses of the curves in Fig. 1, it is evident that Steinmetz's formula giving the relation between the hysteresis-loss and the maximum induction holds for nickel and annealed cobalt up to an induction of 3000 C.G.S.; it holds for cast cobalt and

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*) Fleming and Dewar, loc. cit.

tungsten steel up to 8000 C.G.S.; and lastly for Swedish iron, it fails beyond an induction of 18000 C.G.S. If, however, the specimens are cooled in liquid air, the applicable range of the law for induction is notably extended, as may be seen from Fig. 1.

As regards the residual magnetism, the cooling always increases it in a marked degree.

(*d*) **Hysteresis-loss in Nickel Steels.**

The hysteresis of nickel steels was studied at ordinary temperature, and seven of them at liquid air temperature. The results are given in Table IV and in Fig. 2 a, b.

TABLE IV.

NICKEL STEELS.

	Ordinary temperature.				Liquid air temperature.			
70.32%	H	2.1	3.4	31.2	H	2.5	4.9	30.2
	B	2675	7069	11370	B	2628	6850	11550
	W	886	3510	5353	W	9841	4140	7494
50.72%	H	3.9	4.6	38.9				
	B	4104	6790	13910				
	W	2015	4300	11160				
46%	H	2.9	4.9	7.0	H	2.6	4.9	6.8
	B	1350	3845	7783	B	919	3493	7677
	W	202	1969	5836	W	1026	1970	6867
36%	H	4.0	9.5	39.7	H	5.8	9.5	31.0
	B	2782	6910	11520	B	2581	6948	12800
	W	1264	5290	9404	W	1654	8000	19303
29.24%	H	0.7	6.9	78.0				
	B	749	2774	419				
	W	14.7	109	155				

		Ordinary temperature.				Liquid air temperature.		
29%	H	1.3	9.7	33.7	H	5.0	14.5	22.6
	B	1099	2807	3654	B	507	2132	5188
	W	106	395	393	W	79	2271	13120
28.74%	H	0.89	4.96	53.3				
	B	1261	3054	4662				
	W	58	189	322				
28.32%	H	46.5	218.6	—	H	11.8	19.3	57.2
	B	673	1184	—	B	1938	3964	8394
	W	4.5	16	—	W	1888	7439	28060
26.64%	H	25.3	62.3	148.7	H	14.5	23.2	60.2
	B	64	173	354	B	1552	3406	8076
	W	51	276	703	W	1396	7864	36900
24.40%	H	35.6	85.0	126				
	B	94	215	295				
	W	153	511	731				
24.04%	H	30.3	102.7	244.6	H	17.1	29.6	89.4
	B	331	608	926	B	1180	3212	8783
	W	1110	2586	4108	W	1309	10520	63550

The hysteresis-loss of nickel steels at ordinary temperature is generally small compared with other ferromagnetic metals. The values for reversible alloys are, however, comparable with those of nickel; but for irreversible alloys, they are all very small. Especially nickel steel of 28.32% does not almost enclose any area, giving only 16 ergs for an induction of 1200 C.G.S. If the alloy has a greater value for induction, it will be very useful for the construction of transformers. Thus the magnetic state of the irreversible nickel steels corresponds to that of ferromagnetic metals at high temperatures. As seen from Fig. 2 a, the Steinmetz's formula does not apply, except for very weak inductions.

If the alloys be cooled in liquid air, the hysteresis-loss increases. With irreversible alloys, the increase is enormous.

The applicable limit of Steinmetz's formula becomes greatly extended. Thus we may say, as in the case of the pure metals, that the cooling in liquid air hardens the specimens magnetically.

As regards the residual magnetism, the cooling considerably increases it.

(*e*) **Length Change of Ferromagnetic Metals.**

Table V and Fig. 3 a, b give the observed changes of length at the temperatures of room and of liquid air. Here $\frac{\delta l}{l}$ denotes the elongation per unit of length.

TABLE V.

SWEDISH IRON.

$t=24.5°C$		$t=-186°C$		$t=29.0°C$	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
4.0	0.21	3.0	0.9	4.0	0.7
8.5	2.7	5.3	1.5	5.1	1.6
21.7	3.5	20.0	3.2	11.7	3.4
72.4	3.3	66.5	3.2	37.0	4.2
123.5	2.4	165.0	0.9	104.0	3.3
217.5	0.13	274	−2.0	214	1.1
326	−2.3	396	−4.5	313	−0.8
483	−4.8	565	−7.6	478	−3.3
640	−6.2	—	—	642	−4.5
792	−7.0	814	−10.2	839	−5.1

TUNGSTEN STEEL.

$t=23.2°C$		$t=-186°C$		$t=30.7°C$	
H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$
10.0	0.2	17.6	0.9	13.7	1.0
13.9	1.5	30.0	3.1	20.7	3.1
31.0	3.5	91.0	4.3	45.7	4.3
81.0	4.6	174	4.3	112.3	4.8
209	4.4	287	3.4	174.2	4.5
393	3.4	366	3.1	363	3.4
507	2.6	525	2.3	527	2.6
671	2.4	587	2.1	640	2.3
818	2.1	827	1.5	848	1.9

NICKEL.

$t=19.5°C$		$t=-186°C$		$t=14.0°C$	
H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$
5.4	−2.3	3.6	−0.8	5.0	−1.5
10.0	−6.5	9.6	−2.5	7.6	−4.0
18.3	−12.1	16.0	−7.4	13.4	−8.8
32.2	−19.4	31.2	−15.9	29.2	−18.0
75.0	−29.5	74.9	−24.4	59.3	−26.4
145.8	−34.7	138.4	−28.5	110.4	−32.2
243.6	−36.7	252.6	−31.7	215.5	−36.0
353	−37.3	441	−34.9	387	−37.2
492	−37.7	662	−37.9	485	−37.4
796	−38.0	800	−39.4	772	−37.7

CAST COBALT.

$t=20$°C		$t=-186$°C		$t=20.0$°C	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
14.3	−1.1	9.4	−0.3	15.6	−1.1
33.2	−4.2	30.0	−3.3	33.5	−3.5
62.3	−7.5	64.2	−7.5	63.4	−6.4
106.5	−9.3	126.4	−10.2	124.3	−7.7
167.1	−9.3	234.7	−11.7	231.3	−7.1
217.7	−8.5	350	−10.9	449	−5.7
348	−6.1	465	−9.8	465	−3.8
498	−4.0	616	−8.7	616	−1.5
762	−0.2	749	−7.2	755	−0.1

ANNEALED COBALT.

$t=13.5$°C		$t=-186$°C		$t=25.5$°C	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
31	−0.1	95	−0.3	59	−0.2
46	−0.2	167	−1.1	98	−0.9
86	−1.0	312	−2.7	153	−1.7
142	−1.8	422	−3.4	268	−3.3
224	−2.8	512	−4.5	444	−6.1
347	−4.3	635	−6.1	538	−7.6
498	−6.1	755	−7.4	717	−10.3
647	−7.9	772	−7.6	869	−12.4
800	−9.8				

In Swedish iron and tungsten steel, cooling by liquid air decreases the elongation of the metals; the change in tungsten steel is very small, but in Swedish iron, it is relatively large. In nickel, the contraction is diminished by cooling to a field of 670 C.G.S.; but it is increased in stronger fields. In cast cobalt, the contraction is considerably increased, except in weak field, where a slight decrease of contraction is observed. In annealed cobalt, the contrary is the case; the contraction is always diminished.

With tungsten steel and nickel, the magnetic changes of length before and after the cooling coincide with each other. But in Swedish iron, the elongation after cooling becomes greater than that before cooling. In cast cobalt, the magnetic contraction after cooling slightly decreases, as compared with the elongation before cooling; but with annealed cobalt, the contrary is the case, except in weak field.

The above results for Swedish iron, nickel and annealed cobalt agree with those obtained by us* with rods of these metals. The change of elongation of tungsten steel in high fields does not coincide with that of our former experiment. But the change being very small, the discrepancy may be accounted for by taking into consideration the demagnetizing force, with which our former experiment was not concerned.

(*f*) Length Change of Nickel Steels.

The observed changes of length are given in Table VI and in Fig. 4 a, b, c, d, e, f, g, h, i.

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*) K. Honda and S. Shimizu, loc. cit.

TABLE VI.

NICKEL STEEL 70.32%.

$t=22.0°C$		$t=-186°C$		$t=26.5°C$	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
3.0	0.6	3.0	0.7	2.9	0.9
8.3	3.2	19.0	5.2	20.2	5.3
21.1	6.1	32.8	8.6	67.9	10.4
45.9	9.2	85.3	11.1	121.2	11.6
109.4	11.2	106.8	12.1	280.1	11.9
232.6	11.7	228.7	12.8	422	12.0
392	11.8	334	12.9	499	12.0
546	11.9	473	13.0	639	11.9
663	11.7	631	12.9	802	11.9
791	11.6	763	12.6		

NICKEL STEEL 50.72%.

$t=26.5°C$		$t=-186°C$		$t=27.5°C$	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10$
3.8	0.6	3.8	0.4	5.0	1.0
6.8	2.6	6.8	1.9	9.9	4.3
11.3	5.5	13.0	5.1	44.2	14.5
23.8	10.2	41.0	12.8	102.7	19.8
56.6	16.0	106.0	20.7	236.0	22.8
182.8	22.1	207.2	24.8	363	23.5
280.2	23.0	351	26.4	482	24.1
449	24.0	506	26.7	673	24.7
561	24.2	665	26.7	783	24.9
695	24.3	835	26.8		

NICKEL STEEL 46%.

$t=20.0°C$		$t=-186°C$		$t=21.0°C$	
H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$
4.0	0.3	5.0	0.9	4.0	0.6
7.0	2.8	7.7	2.8	4.8	1.2
15.5	6.2	26.4	9.2	9.4	4.0
76.3	18.5	82.0	20.4	28.1	10.5
168.0	22.7	113.0	22.0	88.7	19.0
255.5	23.8	310	28.6	207.9	22.8
440	24.8	522	29.5	326	23.7
608	25.3	728	30.7	442	24.0
760	25.4			603	24.4
				746	24.4

NICKEL STEEL 36%.

$t=20.0°C$		$t=-186°C$		$t=14.0°C$	
H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$
5.1	0.3	5.6	0.6	5.3	0.3
10.2	2.7	10.4	1.4	13.0	3.3
37.8	8.0	28.2	5.1	27.9	6.6
101.4	13.5	76.3	14.0	71.9	11.8
205.9	16.0	186.4	23.8	174.8	15.5
363	17.4	289.8	26.5	298	16.8
503	18.4	428	28.8	441	17.6
616	19.0	587	29.8	592	18.6
756	20.3	738	30.5	717	19.3

NICKEL STEEL 29.24%.

$t=19.5$°C		$t=-186$°C		$t=23.6$°C	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
16.0	0.6	18.5	0.3	20.0	0.3
55.0	1.0	26.0	0.9	52.6	1.7
93.3	1.7	66.8	2.7	101.9	3.2
149.8	3.4	142.2	6.0	171.8	4.9
291.8	3.6	264.0	9.6	304	7.7
441	5.3	422	13.1	444	9.8
591	6.7	524	15.0	565	11.5
699	7.8	675	16.5	708	13.1
897	9.7	837	17.8	801	13.9

NICKEL STEEL 29%.

$t=11.5$°C		$t=-186$°C		$t=14.0$°C	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
15.4	1.1	22.9	0.1	18.8	0.3
36.9	1.9	49.3	2.5	31.8	1.1
83.6	2.7	105.7	7.7	59.6	3.2
147.6	3.4	206.9	12.6	122.2	5.6
323	4.9	313	16.4	349	11.1
472	6.9	412	18.0	470	12.8
692	9.0	555	20.1	633	14.5
850	10.3	681	21.6	770	15.8

NICKEL STEEL 28.74%.

$t=22.5^\circ\mathrm{C}$		$t=-186^\circ\mathrm{C}$		$t=21.5^\circ\mathrm{C}$	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
11.4	0.6	35.0	1.0	16.0	0.2
46.7	1.7	81.0	4.0	37.0	1.6
92.6	2.4	138.7	6.7	76.0	3.5
155.7	2.7	184.7	8.2	133.2	5.6
281.0	4.2	248.0	10.3	250	8.5
419	5.6	327	11.8	337	10.3
681	7.2	519	15.4	457	12.4
782	8.6	687	17.7	633	14.7
		822	19.4	820	16.7

NICKEL STEEL 28.32%.

$t=20.0^\circ\mathrm{C}$		$t=-186^\circ\mathrm{C}$		$t=21.5^\circ\mathrm{C}$	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
21.3	0.2	27.0	0.8	15.0	0.2
50.2	0.6	39.0	1.5	41.5	1.5
85.3	0.8	66.2	2.7	92.0	3.0
169.0	1.2	101.0	4.4	144.4	4.9
281.6	2.0	231	9.4	275	8.3
378	3.0	368	12.9	420	11.2
455	3.6	454	14.3	599	14.0
601	4.8	618	16.2	788	16.4
810	6.1	826	18.3	878	17.4

NICKEL STEEL 26.64%.

$t=24.5$°C		$t=-186$°C		$t=21.0$°C	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
28.7	0	19.6	0.2	20.0	0.3
81.3	0	42.0	1.6	47.2	2.4
118.2	0	92.6	4.8	94.0	5.7
180.0	0.08	145.0	6.9	168	9.3
302	0.13	255	10.8	300	12.8
489	0.15	353	12.9	408	14.9
680	0.17	490	15.4	530	16.9
890	0.21	593	16.9	668	18.2
		774	17.7	778	18.8
		935	19.5		

NICKEL STEEL 24.40%.

$t=25.0$°C		$t=-186$°C		$t=20.5$°C	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
—	—	22.7	0.1	19.0	0.3
—	—	50.8	1.4	32.0	0.9
—	—	91.0	3.1	78.2	3.4
118	0	156.5	5.2	149	6.8
236	0	295	9.3	240	9.5
367	0.02	405	11.2	362	12.2
494	0.08	544	13.1	484	14.6
705	0.10	640	13.9	621	16.3
886	0.11	839	16.9	795	18.4

NICKEL STEEL 24.04%.

$t=21.0°C$		$t=-186°C$		$t=23.0°C$	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
22.9	0	34.3	0.7	35.3	1.0
76.5	0.1	65.7	2.5	66.7	2.9
196.6	0.2	124.0	5.9	112.0	5.4
281.7	0.3	238.5	9.9	253	10.0
429	0.35	334	13.3	398	12.7
600	0.6	468	17.8	508	14.4
808	0.7	622	21.6	695	15.9
		835	25.6	858	16.9

The effect of cooling on the magnetic elongation in nickel steels is exactly parallel to the same effect on magnetization. In nickel steels containing percentages of nickel greater than 28.74%, the elongation is diminished in weak fields and increased in the strong, by cooling them in liquid air; with other nickel steels, the initial decrease of elongation vanishes.

The ratio of the elongation in liquid air to that at ordinary temperature increases in strong fields, as the percentages of nickel decreases. In 36% Ni, it amounts to about 1.6 in H=500 C.G.S.; and in 28.32% Ni, to 3.7, and in 24.40% Ni to 160 for the same field.

For reversible nickel steels, the elongations after and before cooling coincide with each other. The elongation of other nickel steels, once cooled in liquid air, is always greater than that before cooling. With 26.64% and 24.40% alloys, the elongation is even increased, by heating it to the ordinary temperature.

25% nickel steel does not sensibly elongate at ordinary temperature nor in liquid air.

(*g*) Change of Density by Cooling.

The density of the irreversible nickel steels at ordinary temperature suffered a permanent change, if they were once dipped in liquid air. This singular fact was first observed by Hopkinson*. The following table contains the observed values of density:—

TABLE VII.

Alloys	28.32% Ni	26.64% Ni	24.40% Ni	24.04% Ni
Before cooling	8.15	8.16	8.13	8.06
After cooling	8.01	7.99	8.06	7.94

Thus the density is diminished, by cooling them in liquid air; M. Ch. Ed. Guillaume† specially investigated this point, by measuring the coefficient of thermal expansion at low temperatures. He found that the irreversible nickel steels expand on being cooled in solid carbon dioxide and again expand when heated to ordinary temperatures. Hence the effect of cooling is to doubly diminish the density of the alloys.

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*) Hopkinson's Original Papers Vol. II, p. 240.

†) Guillaume, Bulletin de la Société d'Encouragement, mars 1898, p. 273.

II. SECOND EXPERIMENT.

To obtain a constant low temperature lying between the ordinary and the liquid air temperatures, a method of slow cooling was applied. The specimen-holder in the former apparatus was water-tightly covered with a brass cylinder, and a suitable amount of liquid air was poured into the interspace between the cylinder and the DEWAR tube. The temperatures above −15°C were, however, obtained by dipping the specimen directly into a freezing mixture (snow and common salt) contained in the DEWAR tube. The experiment was commenced with the specimen in the annealed state, and the measurements at successively decreasing temperatures were made. During one set of observations, which usually required 7 or 8 minutes, the temperature was fairly constant and its change did not exceed one degree in the most unfavorable case. Since the cooling was very slow and the specimen was doubly enclosed in copper and brass tubes, the temperature of the specimen may be regarded as constant throughout its entire length.

The temperature of the specimen was measured by a thermoelectric couple of platinum and german silver. The wires were insulated with a thin caoutchouc tube. One of the junctions was brought in contact with the specimen at its middle, while the other was insulated with asbestos papers and inserted in a copper tube. This tube was dipped into the water bath, and its temperature was observed with a thermometer placed in the bath. The thermoelectric current was measured with a low resistance galvanometer. The calibration of the galvanometer was made by using a mercury thermometer and a petroleum-ether thermometer.

Since the character of the pure metals and the reversible nickel steels were not much altered by cooling them in liquid air, the measurements of the magnetization and the magnetic change of length at the intermediate temperatures were confined to only the irreversible nickel steels, that is, those, whose percentage-contents of nickel were less than 29.24% (excluding 25% Ni).

(*a*) Magnetization of Nickel Steels.

The observed values of the intensity of magnetization are given in Table VIII. Here H and I have the same meaning as before.

TABLE VIII.

NICKEL STEEL 29.24%.

$t=-1.9$°C		$t=-32.5$°C		$t=-62.5$°C	
H	I	H	I	H	I
0.15	10	0.16	8	0.16	15
0.40	41	0.23	48	0.66	24
0.79	79	0.49	105	2.26	76
1.34	110	1.10	167	5.40	152
3.19	172	2.19	232	9.01	227
6.88	226	3.89	298	17.07	341
12.33	264	11.22	381	22.65	391
22.81	287	12.49	453	33.8	450
46.2	297	67.6	530	61.9	561
75.4	301	120.9	565	120.0	670
151.5	306	188.0	583	234.7	758
313	311	323	590	329	811
448	315	369	596	408	812

NICKEL STEEL 29%.

$t=12.4°C$		$t=-37.5°C$		$t=-121.8°C$	
H	I	H	I	H	I
0.21	18	0.24	24	0.42	8
0.61	69	0.52	52	1.93	53
0.98	109	1.01	107	3.93	107
1.84	164	2.30	203	9.87	215
3.00	214	4.19	287	16.30	309
5.34	273	9.20	405	22.58	376
13.17	352	15.50	475	45.5	506
26.62	375	31.1	521	77.3	614
66.4	382	62.2	539	160.5	740
161.2	387	126.9	544	280.8	813
302	390	261.5	546	395	845
438	392	416	548		
	3.5		5		47

NICKEL STEEL 28.74%.

$t=-10.4°C$		$t=-54.5°C$		$t=-108.0°C$	
H	I	H	I	H	I
0.22	16	0.25	13	1.24	12
0.43	42	0.63	62	4.29	64
0.95	95	1.83	153	9.05	153
2.09	154	2.95	205	14.64	261
3.69	210	5.17	275	21.40	359
9.68	317	10.99	382	29.83	424
19.82	383	25.02	481	49.2	536
32.0	402	69.9	542	66.9	607
64.8	415	189.0	550	131.2	741
189.0	419	325	550	218.0	827
298.8	420	420	551	310	874
445	423			380	904
	2.4		3.8		91

NICKEL STEEL 28.32%.

$t=-12.5°C$		$t=-45.0°C$		$t=-79.5°C$	
H	I	H	I	H	I
0.31	24	0.16	18	0.45	16
0.86	55	0.50	62	0.96	40
2.63	101	1.41	121	2.79	86
4.73	128	3.33	186	6.24	142
14.98	159	7.00	252	10.98	203
32.9	170	15.46	301	17.85	266
75.3	180	28.78	315	30.2	336
180.6	193	73.4	321	63.2	417
332	205	168.9	325	90.0	451
450	211	345	327	191.4	502
		438	328	305	526
				419	542
	0.5		0.4		19.5

NICKEL STEEL 26.64%.

$t=-9.6°C$		$t=-36.5°C$		$t=-80.0°C$	
H	I	H	I	H	I
10.0	2.8	3.95	9	2.15	12
20.2	7.0	11.38	24	5.96	39
39.3	17.2	24.95	58	11.60	92
94.6	32.3	36.6	82	16.43	142
195.7	47.8	55.9	122	31.0	290
312	60.0	129.8	168	50.1	386
470	71.9	222.0	212	63.0	437
		332	247	97.2	524
		446	275	169.5	623
				224.6	726
				321	736
				392	770
	15.3		64		166

NICKEL STEEL 24.40%.

t=6.5°C		*t*=−13.9°C		*t*=−68.7°C		*t*=−105.5°C	
H	I	H	I	H	I	H	I
11.4	1.9	5.1	2.1	3.0	7	2.6	9
16.9	3.2	11.5	6.1	10.4	28	9.2	38
27.2	5.4	19.1	13.0	16.8	57	18.5	108
38.5	7.7	28.2	21.2	26.0	119	25.1	176
55.9	11.1	43.2	33.5	35.8	187	32.1	268
98.9	16.1	64.5	43.7	57.3	283	45.6	339
193.9	24.5	102.7	58.4	69.6	335	75.7	481
291.4	31.5	170.4	75.8	104.9	401	106.8	561
391	37.2	255.5	90.5	177.0	488	166.2	651
		323	99.2	297.9	569	226.4	717
				407	618	320	786
						396	826
	7.3		33.6		192		226

NICKEL STEEL 24.04%.

t=−6.2°C		*t*=−13.2°C		*t*=−60.8°C		*t*=−99.0°C	
H	I	H	I	H	I	H	I
5.9	3.2	4.4	4	4.1	9	2.6	8
13.1	9.4	11.6	11	11.2	32	7.3	24
26.2	26.0	25.2	37	20.6	82	16.1	66
43.7	46.8	40.5	71	34.1	191	21.4	123
74.1	72.8	79.4	123	49.1	285	29.3	223
134.1	95.3	159.5	175	66.2	363	49.2	367
228.8	118.8	295.4	219	101.1	461	62.8	452
342	137.3	393	239	184.8	580	80.4	533
457	148.3	450	250	255.6	661	112.5	629
				400	713	240.8	807
						282.2	842
						323	870
	50.4		87		231		266

In weak fields, the intensity of magnetization gradually increases, as the temperature falls, till it reaches a maximum, and then gradually decreases. As the field is increased, this maximum recedes towards lower temperatures, and beyond 50 C.G.S., the maximum altogether disappears. These changes are common to nickel steels of 29.24% to 28.32% Ni. In 24.04%, 24.40% and 26.64% Ni, the maximum does not appear from the outset, i.e., as the temperature falls, the intensity of magnetization at first rapidly increases and soon approaches to an asymptotic value for every magnetizing field.

(*b*) Length change of nickel steels.

The magnetic change of length of nickel steels is given in Table IX and in Fig. 4 c, d, e, f, g, h, i, from which the curves of the change of length for constant fields are obtained and drawn in Fig. 5 a, b, c, d, e, f, g.

TABLE IX.

NICKEL STEEL 29.24%.				NICKEL STEEL 29%.			
$t=-0.3°C$		$t=-70.0°C$		$t=-38.0°C$		$t=-123.3°C$	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
4.7	0.3	4.2	0.2	3.4	0.7	10.8	0.2
18.6	1.5	15.3	0.8	12.3	2.8	40.5	1.8
65.1	2.0	46.1	2.2	36.9	4.7	116.5	5.6
118.6	2.7	61.1	3.8	72.3	5.6	241.2	9.3
251.6	4.0	177.7	7.7	175.8	6.5	321	10.6
333	4.8	287.6	9.8	302	7.0	394	11.8
469	5.7	404	11.8	415	7.7		

NICKEL STEEL 28.74%.

$t=-8.3°C$		$t=-53.0°C$	
H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$
6.8	0.8	2.7	0.3
17.2	2.1	9.9	1.6
72.9	3.5	53.2	5.1
217.3	4.8	175.3	6.7
316	5.7	299	7.7
430	6.8	418	8.6

NICKEL STEEL 28.32%.

$t=-45.2°C$		$t=-77.5°C$	
H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$
15.8	1.4	11.1	0.2
56.0	2.2	25.7	1.0
149.3	3.2	34.9	1.4
248.3	4.0	79.5	2.6
353	5.1	193.3	3.9
443	5.9	286.6	5.1
		417	6.4

NICKEL STEEL 26.64%.

$t=-39.5°C$		$t=-78.4°C$	
H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$
45.7	0.3	26.6	0.5
127.9	1.0	67.8	2.0
268.0	2.0	166.7	4.8
442	3.8	266.5	7.0
		390	9.5

NICKEL STEEL 24.40%.

$t=-69.2°C$		$t=-97.7°C$	
H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$
21.4	0.1	28.8	0.5
47.8	0.2	67.0	1.9
152.9	2.2	177.5	3.8
240	3.5	281	6.6
336	4.8	389	7.9
411	5.3		

NICKEL STEEL 24.04%.

$t=-2.0°C$		$t=-64.0°C$		$t=-96.0°C$	
H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$
40.9	0.1	43.5	0.5	20.5	0.1
124.4	0.2	114.0	2.0	44.2	1.0
266	0.6	217.3	3.7	125.4	3.4
463	1.1	402	6.6	216.8	5.6
				318	7.7
				412	9.3

From these numbers, we find a parallelism between the change of magnetization and that of the length-change. In weak fields, the change of length gradually increases as the temperature falls, till it reaches a maximum, and then decreases. As the field becomes stronger, the maximum elongation is displaced in lower temperatures, and at last vanishes. These changes are common to nickel steels of percentages higher than 28.32% ; for percentages lower than 26.64%, the elongation for a constant field at first increases gradually and then rapidly, soon approaching an asymptotic value, as the temperature falls.

III. THIRD EXPERIMENT.

In the third series of experiments, the magnetization was measured at different stages of ascending as well as descending temperatures, the measurement of the change of length by magnetization being left for future experiments.

The heating was effected by means of an electric current; a porcelain tube (external diam.=1.7 cm, internal diam.=1.05 cm, length=47 cm) was covered with a few layers of asbestos paper, and the lower part (36 cm) was wound anti-inductively with a platinum wire 0.4 mm thick at the rate of 2 turns per cm. It was then wrapped in asbestos papers to a thickness of about 5 mm. To the upper end of the porcelain tube, a brass flange was fixed, while to its lower end, a short porcelain cylinder was inserted tightly, so as to arrest air currents. The length of this cylinder was so chosen that when the tube was placed in the right position in the central line of the magnetizing coil, the ovoid occupied the central position of the coil. The magnetizing coil was provided with a water-jacketed arrangement, and a coil for the compensation of the vertical component of earth field.

The temperature of the ovoid was measured with a platinum rhodium-platinum junction. One of the junctions was placed in contact with the specimen at a point a quarter of the distance from the upper end of the ovoid, the rest being well insulated with asbestos paper. The interspace between the lead wire and the wall of the porcelain tube was tightly filled with asbestos fibres, and thus protected as much as possible from the convection current. The other junction was arranged as in the second experiment. The thermoelectric current was measured with a d'ARSONVAL galvanometer from KEISER and SCHMIDT, the reading of which was corrected by the authors with a mercury thermometer containing nitrogen below 550°C, and by Professor NAGAOKA and Mr. S. KUSAKABE with the melting point of sodium chloride. A low resistance galvanometer was, at the same time, employed to measure the temperatures lower than 200°C. A simple connection permitted us to pass the thermoelectric current through the d'ARSONVAL or the low resistance galvanometer, as the case might be.

The experiment was conducted in the following order. The adjustments of the magnetometer and the coils, as described in the first experiment, were effected; the heating coil with the specimen was then placed in the right position. The magnetization at the temperature of the room was first determined; then a current from a dynamo was passed through the heating coil, till the temperature of the specimen became constant. The direct effect due to the current in the heating coil was tested by breaking or reversing the current. The small deflection of the magnetometer, when there was any, was completely eliminated by altering the form of the lead wires. The demagnetization by reversals, while the heating current was passing, showed no trace of residual magnetism, which indicates that the magnetization due to the heating current was insensibly small. When the temperature became constant, the magnetizations at gradually increasing fields were measured. Another stronger current was next sent through the heating coil, and the same processes were repeated as before. In this way, we measured the magnetization in the stage of ascending temperature, and then that in the descending stage. During each set of observations, the temperature was fairly constant, and even in very unfavorable cases, it did not exceed 2 degrees. The temperature was always noted both before and after each experiment, and the mean was taken. When a series of experiments was finished, the specimen was taken out of the coil, and the compensation tested. Excepting in a few cases, we found the compensation undisturbed; when, however, the disturbance was such as to require a correction, it was uniformly distributed.

In the present experiment, the strength of the heating current and the temperature thereby caused were as follows:—

Current	1.8 amp	2.9	3.8	4.7	5.5
Temperature	100°C	300	600	900	1200

The heating of nickel steels protected in the manner above described showed only a trace of surface-oxidation, if the temperature did not exceed about 800°C. If, however, the temperature was raised to 1200°C, the surface-oxidation became considerable, so that the heating of some specimens was stopped at about 800°C, if there was nothing of special importance to be gained by heating them above that temperature.

(a) Magnetization of ferromagnetic metals.

The ovoids were first cooled in liquid air; the observations at ordinary and then at higher temperatures were taken; the results are given in Table X.

TABLE X.

SWEDISH IRON.

t=714°C		t=736°C		t=757°C		t=761°C	
H	I	H	I	H	I	H	I
0.13	49	0.13	40	0.05	50	8.1	11.8
0.26	115	0.79	220	3.29	121	75.5	39.0
0.50	338	18.42	373	29.39	166	188.9	64.5
1.39	533	115.6	493	125.8	211	333	85.3
2.48	597	258.0	542	305	241	437	97.6
22.46	744	398	561	425	250		
258.6	829						
377	834						

t=772°C		t=849°C		t=1009°C		t=1214°C	
H	I	H	I	H	I	H	I
52	6.3	128	2.0	99	1.7	92	1.4
140	15.4	300	3.4	280	3.4	286	2.8
281	23.1	443	3.9	439	3.9	442	3.1
444	29.0						

NICKEL.

t=205°C		t=319°C		t=362°C		t=410°C	
H	I	H	I	H	I	H	I
1.58	73	1.77	99	32.8	0.8	55	1.1
5.62	190	9.06	176	182.4	5.3	179	4.4
18.83	314	31.0	204	363	9.0	345	6.5
85.7	390	124.5	210	481	10.8	479	8.1
207.4	398	285	213				
334	401	464	215				
447	403						

t=518°C		t=678°C		t=874°C		t=1149°C	
H	I	H	I	H	I	H	I
183	3.8	182	3.5	236	4.6	129	2.8
366	6.3	343	5.4	363	5.4	349	5.1
478	7.3	477	6.4	479	5.9	481	5.7

ANNEALED COBALT.

t=185°C		t=307°C		t=428°C		t=546°C	
H	I	H	I	H	I	H	I
13.45	49	3.87	45	3.22	22	4.27	57
19.52	96	7.43	112	8.23	83	7.13	141
32.4	198	14.69	319	13.41	185	13.62	406
63.5	325	37.6	570	21.46	307	22.43	547
94.3	411	92.8	770	57.7	514	59.9	710
184.1	568	195.7	913	119.1	662	126.7	832
279.2	677	319	998	240.1	812	253.2	928
376	758	370	1018	379	906	374	978

$t=619$°C		$t=770$°C		$t=919$°C		$t=1060$°C	
H	I	H	I	H	I	H	I
2.48	32	2.40	50	1.26	46	4.14	56
4.79	108	4.45	151	2.55	141	22.03	84
7.88	250	13.21	411	13.83	399	51.1	98
31.31	573	28.15	531	42.20	518	90.0	106
72.1	716	76.0	674	94.4	591	212.5	126
128.5	806	134.0	749	184.9	639	333	136
271.4	909	262.9	823	291.6	665	439	140
378	951	386	856	400	674		

$t=1066$°C		$t=1074$°C		$t=1109$°C		$t=1219$°C	
H	I	H	I	H	I	H	I
2.25	25	7.5	10.6	142	3.0	130	2.2
7.54	44	41.7	19.4	324	6.1	284	3.6
46.8	62	172.1	32.8	446	7.7	443	4.3
149.6	87	343	41.9				
244.1	100	446	45.0				
436	107						

The magnetization of iron and nickel at high temperatures is so well known that it is superfluous to give all the numerical data obtained by our experiment. Hence in the above table, the numbers for iron and nickel are limited to those at very high temperatures, in which they become of interest.

Swedish iron. The magnetization in constant temperature was measured at 20 different temperatures in ascending as well as descending stages; the curves of magnetization were then plotted against the internal field. These curves were cut by an ordinate of constant field. The curves of magnetization in a constant field plotted against the temperature were thus obtained, and are given in Fig. 6 a.

The change of magnetization of Swedish iron by temperature rise was found to agree well with the results obtained by previous investigators*. The weak magnetization beyond the critical point, as first observed by CURIE, was also noticed. Here the magnetization at different temperatures ranging from 800°C to 1200°C diminishes very slightly as the temperature rises. Thus the meaning of the critical point becomes vague; H. DU BOIS defines this temperature to be a point of inflexion in the curve of magnetization to temperature; but it is more convenient to define the temperature as the point of the maximum curvature. The critical temperature so defined is, in the case of Swedish iron, 780°C for H=400 C.G.S. It is also to be observed that the critical temperatures for ferromagnetic metals and alloys depend more or less upon the strength of the field.

The magnetization in a stage of descending temperatures falls a little short of the magnetization in ascending temperatures for the same field and temperature. But at ordinary temperatures, they coincide with each other. Combining the above results with those of the magnetizations at the liquid air temperature, we obtain a hysteresis curve with regard to temperature, whose lower range is considerably extended by the present experiment.

Annealed Cobalt. As in the case of Swedish iron, the curves of magnetization to temperature were obtained, and are given in Fig. 6 b.

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*) J. HOPKINSON, Phil. Trans. CLXXX, p. 443, 1889; Proc. Roy. Soc. XLIV, p. 317, 1888. LYDALL and POCKLINGTON, Proc. Roy. Soc. LII, p. 228, 1893. D. K. MORRIS, Phil. Mag. XLIV, p. 213, 1897. LEDEBOER, C.R. CVI, p. 129, 1888. TOMLINSON, Proc. Phys. Soc., IX, p. 181, 1888. CURIE, C.R. CXV, p. 805, 1892; CXVIII, p. 796 and 859. WILDE, Proc. Roy. Soc. L, p. 109, 1891. KUNZ, Elekt. Zeits., XV, p. 194, 1894. WILLS, Phil. Mag. L, p. 1, 1900. NAGAOKA and KUSAKABE, Jour. Coll. Sci., XIX, Art. 9., 1904.

The magnetization of annealed cobalt at high temperatures was first observed by Professor NAGAOKA and Mr. KUSAKABE*. The present results generally agree with those obtained by them, but in our case, the cooling in liquid air slightly altered the the magnetic property. In Fig. 6 b, the point corresponding to the magnetization in liquid air is also included.

As the temperature rises from −186°C, the magnetization in a constant field increases at first slowly and then rapidly, till it reaches a maximum at about 300°C, after which it decreases. The magnetization reaches a small minimum, and then begins to increase, and after passing through another maximum, rapidly decreases, reaching its critical point at 1090°C for $H=400$. The descending branch of the curves cuts the ascending branch at about 850°C from downward to upward; but its general course is similar to that of the ascending curve. The minimum point in the ascending branch is about 450°C, and nearly coincides with the singular temperature observed by us in the change of length by magnetization†; at this temperature the sign of the length change is reversed for all fields.

It is also to be noticed that the course of the curve beyond the critical point is nearly parallel to the axis of temperature.

Nickel. The specimen, which was first cooled in liquid air, was heated and the magnetizations at ten different ascending temperatures were observed; since the dynamo stopped, when the temperature attained 1150°C, the magnetizations at decreasing temperatures were not taken as in the other cases, except for the maximum field only.

The curves of the magnetization to the temperature are

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*) NAGAOKA and KUSAKABE, loc. cit..

†) HONDA and SHIMIZU, Jour. Coll. Sci., XIX, Art. 10, 1903; Phil. Mag. VI, p. 392, 1903.

drawn in Fig 6 c, in which the results of the first experiment were also included. The character of the change of magnetization by heating coincides with the results obtained by the former investigators*. Here the range of the temperature is considerably extended on the negative side of zero temperature. It is remarkable that though the magnetization falls very rapidly near the critical temperature 360°C, its further decrease is very small, and even at 1200°C, a magnetization of about 6 C.G.S. for $H=400$, is still observed. This important phenomenon was first observed by CURIE.

(*b*) Magnetization of Nickel Steels.

In nickel steels, the magnetic state after cooling in liquid air slightly changes as the time proceeds. In some alloys, it does not return to its initial state, when they undergo a cyclic change of temperatures between −186°C and 1100°C. This change of character is greater in the irreversible alloys than in the reversible.

The magnetization of the alloys at different temperatures presents a striking contrast between the reversible and the irreversible alloys. Some of the interesting results had already been obtained by previous investigators†.

The manner in which the magnetization of the reversible nickel steels changes with the temperature is similar to that of nickel, as given in Table XI.

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*) J. HOPKINSON, loc. cit. CURIE, loc. cit. NAGAOKA and KUSAKABE, loc. cit.

†) H. BECQUEREL, C.R. XCIII, p. 794, 1881; J. HOPKINSON, Pro. Roy. Soc., XLVII, p. 23, 1890, and XLVIII, p. 1, 1890; H. Le CHATELIER, C.R., CX, p. 283, 1890 and CXI, p. 454, 1890; H. TOMLINSON, Pro. Roy. Soc., LVI, p. 103, 1894; F. OSMOND, C.R., CXVIII, p. 532, 1894, and CXXVIII, p. 304, 1396, 1899; Ch. Ed. GUILLAUME, C.R., CXXIV, p. 176, 1515, 1897; CXXV, p. 235, 1897; CXXVI, p. 738, 1898; Les aciers au nickel, Paris 1898; E. DUMONT, C.R., CXXVI, p. 741, 1898; L. DUMAS, C.R., CXXX, p. 357, 1900.

TABLE XI.

NICKEL STEEL 70.32%.

$t=11.7$°C		$t=104$°C		$t=410$°C		$t=658$°C	
H	I	H	I	H	I	H	I
0.34	9	0.40	16	0.41	256	35	2.8
1.07	42	1.08	69	1.89	368	132	9.1
1.73	232	1.25	164	8.92	485	276	18.6
4.28	570	1.60	374	31.4	536	476	29.2
12.29	716	2.86	516	64.1	545		
25.09	864	29.5	867	153.5	552		
41.1	947	68.3	944	294.6	565		
76.4	1000	166.1	970	434	573		
193.7	1029	264.6	980				
393	1043	405	989				

$t=733$°C		$t=900$°C		$t=753$°C		$t=11.5$°C	
H	I	H	I	H	I	H	I
48	3.9	125	3.8	40	1.7	0.29	28
100	5.6	305	7.9	137	5.0	1.08	171
248	14.3	491	10.3	304	8.5	4.22	491
469	26.7			488	11.0	21.64	908
						56.3	1008
						204.4	1034
						349	1041
						405	1045

NICKEL STEEL 50.72%.

t= 12.0°C		t= 126°C		t= 296°C		t= 410°C	
H	I	H	I	H	I	H	I
0.54	21	0.95	31	0.76	42	0.40	34
1.91	79	2.90	336	1.27	133	0.70	154
2.70	189	4.30	536	4.44	548	1.67	314
3.29	334	9.54	697	21.39	791	8.81	477
22.68	971	27.40	972	41.9	877	24.43	536
47.5	1123	52.1	1077	91.5	898	57.6	558
108.0	1218	115.9	1146	213.7	913	159.4	565
186.6	1250	215.1	1166	417	921	305	567
309	1263	398	1176			443	579
386	1267						

t=639°C		t=807°C		t=634°C		t=495°C	
H	I	H	I	H	I	H	I
21	0.7	31	1.1	31	0.7	30	0.6
113	3.9	206	6.9	136	4.7	98	3.4
267	8.2	487	11.5	322	9.0	345	10.7
490	11.3			484	11.6	482	13.6

t=431°C		t=263°C		t= 192°C		t= 12.2°C	
H	I	H	I	H	I	H	I
12.7	4.7	0.06	46	0.07	34	0.20	26
34.7	11.5	0.20	169	0.18	432	0.49	87
101.6	31.2	0.45	586	0.70	649	0.77	355
245.1	46.2	85.3	941	6.53	951	0.94	582
402	58.7	269.8	949	24.20	1048	45.7	1235
478	65.1	408	952	72.0	1069	143.0	1259
				253.5	1078	261.7	1264
				390	1082	378	1267

NICKEL STEEL 46%.

t=12.3°C		*t*=131°C		*t*=267°C		*t*=345°C	
H	I	H	I	H	I	H	I
0.78	22	0.78	28	0.59	31	0.42	38
1.83	60	2.56	144	1.29	96	0.82	112
3.40	190	3.21	319	2.71	403	2.51	227
7.49	549	5.11	521	5.40	561	4.59	380
9.87	706	9.71	751	15.11	704	13.46	495
17.70	913	22.80	943	34.8	778	40.2	562
42.9	1113	46.6	1047	78.9	834	135.3	588
80.3	1201	106.6	1114	213.4	851	253.9	593
195.4	1260	264.4	1140	317	852	431	597
375	1276	381	1146	409	854		

t=411°C		*t*=456°C		*t*=624°C		*t*=488°C	
H	I	H	I	H	I	H	I
17	2.8	47	0.6	56	2.0	87	4.5
50	6.2	105	2.8	240	7.3	234	8.7
137	14.6	305	10.0	387	11.6	385	12.5
477	40.8	483	14.2	479	13.4	475	14.2

t=371°C		*t*=318°C		*t*=210°C		*t*=33.2°C	
H	I	H	I	H	I	H	I
12.3	30	0.59	31	0.72	27	1.62	49
18.9	45	1.51	209	1.35	80	2.90	132
45.6	91	5.24	400	2.14	204	5.94	512
190.6	143	11.41	490	5.86	527	17.62	827
347	168	45.2	592	50.95	887	69.6	1120
459	183	198.0	626	169.4	964	161.8	1217
		329	631	284	974	280	1243
		425	638	399	979	369	1252

NICKEL STEEL 36%.

t=10.0°C		*t*=161°C		*t*=225°C		*t*=259°C	
H	I	H	I	H	I	H	I
1.24	30	1.06	55	5.7	33	31.6	0.7
3.51	119	2.23	191	17.8	45	152.2	6.0
4.32	232	3.99	308	48.2	54	355	13.2
7.79	499	12.89	461	259.0	84	497	16.6
32.9	863	54.9	547	478	102		
64.2	954	135.1	563				
176.2	1021	276.5	572				
299	1035	437	578				
419	1039						

t=447°C		*t*=828°C		*t*=423°C		*t*=303°C	
H	I	H	I	H	I	H	I
96	3.3	105	4.7	31	1.8	79	4.2
251	8.4	251	10.5	103	5.7	232	10.5
491	13.5	488	17.1*	283	12.9	363	14.7
				484	18.1	482	17.8

t=218°C		*t*=182°C		*t*=145°C		*t*=10.0°C	
H	I	H	I	H	I	H	I
30.5	14.7	0.26	54	0.21	42	0.31	32
77.4	23.9	1.54	198	0.46	127	0.71	118
160.2	35.5	8.08	335	1.51	242	1.66	314
320	55.3	20.58	364	6.46	459	4.88	556
481	70.6	71.4	379	49.6	582	16.15	801
		250.7	391	151.4	592	112.1	1013
		447	401	292.3	597	247.9	1027
				428	602	302	1028
						375	1029

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*) In this case, the compensation of the magnetizing coil was found to be disturbed and therefore the disturbance was equally distributed over the whole set. This small increase of magnetization is probably due to the impared compensation.

Comparing the above values for ordinary temperature with het corresponding values in the first experiment, we notice that except with 36% nickel steel, the magnetizability of these alloys had slightly changed by the repeated heating and cooling, which the alloys underwent, since the end of the first experiment.

From these results, the curves of magnetization to temperature are obtained and given in Fig. 7 a, b, c, d. In these figures, we have also included the results obtained in our first and second experiments. As seen from the figures, the diminution of magnetization, after the critical point is reached, is very slight; and to judge from the course of the curve, it seems probable that the magnetization does not altogether vanish, till the melting points are reached.

The curves of magnetization at a constant field in the ascending and descending stages of temperature do not exactly coincide with each other when the range of temperature is large, the two curves thus enclosing a small area between them.

As the critical points of these nickel steels for H=400, we give the following values:—

Alloys	70.32%	50.72%	46%	36%
Ascending branch	660°C	490°C	412°C	255°C
Descending branch	——	460°C	395°C	240°C

These values nearly coincide with those of M. Osmond and L. Dumas. Thus the critical point decreases with the percentage content of nickel.

The manner, in which the magnetization of irreversible nickel steels changes with temperature, is very striking. The observed values are given in Table XII.

TABLE XII.

NICKEL STEEL 29.24%.

$t=11.6$°C		$t=140$°C		$t=210$°C		$t=352$°C	
H	I	H	I	H	I	H	I
3.21	30	5.83	31	11.27	57	9.87	56
9.33	103	12.57	109	18.51	162	18.10	161
14.20	200	29.8	299	29.1	276	31.3	275
22.35	355	74.3	433	68.0	428	69.4	399
48.3	507	169.5	566	164.7	566	167.7	518
79.0	604	329	678	280.5	646	308	595
150.5	723	449	729	442	713	445	639
244.2	810						
345	870						
417	902						

$t=499$°C		$t=547$°C		$t=799$°C		$t=466$°C	
H	I	H	I	H	I	H	I
20.3	6.2	51	1.8	51	2.0	52	2.2
56.0	18.9	168	6.1	140	4.8	152	5.8
183.2	57.3	357	10.9	308	9.3	311	12.8
304	80.4	495	13.9	494	12.3	494	13.7
410	94.6						
487	102.5						

$t=299$°C		$t=192$°C		$t=93$°C		$t=12.0$°C	
H	I	H	I	H	I	H	I
31	1.1	31	1.4	45	2.2	0.21	46
105	4.9	103	5.1	107	5.8	1.63	107
256	10.1	254	10.5	272	13.2	5.15	182
376	12.8	375	13.6	494	20.6	27.91	250
497	15.5	494	16.2			95.6	265
						188.7	275
						334	286
						477	295

NICKEL STEEL 29%.

$t=14.3$°C		$t=168$°C		$t=268$°C		$t=383$°C	
H	I	H	I	H	I	H	I
4.35	3	5.95	23	7.43	21	9.85	44
5.31	71	12.60	86	14.55	71	26.24	153
12.31	214	19.61	176	23.40	173	49.3	230
20.76	367	30.5	254	36.1	257	109.7	314
29.1	432	64.5	353	115.4	407	231.1	387
57.5	585	208.7	503	281.5	512	441	446
125.2	717	323	561	434	561		
238.0	815	436	600				
416	889						

$t=465$°C		$t=515$°C		$t=644$°C		$t=799$°C	
H	I	H	I	H	I	H	I
16.9	16	45.7	2.3	54	2.0	94	2.5
45.4	50	161.3	10.8	280	7.7	282	3.6
93.3	96	340	22.9	475	10.3	477	8.9
212.4	161	473	29.9				
321	192						
448	217						

t=601°C		t=405°C		t=206°C		t=12.3°C	
H	I	H	I	H	I	H	I
65	2.3	94	3.4	86	3.4	0.41	78
247	7.3	232	7.4	229	8.0	1.36	182
479	10.4	344	9.0	358	10.7	4.54	302
		476	10.8	473	12.2	17.32	381
						138.4	412
						369.9	426
						466	428

NICKEL STEEL 28.74%.

t=12.3°C		t=87°C		t=143°C		t=228°C	
H	I	H	I	H	I	H	I
3.09	22	3.99	21	5.66	32	3.63	14
7.20	67	8.26	52	10.47	92	10.53	61
14.04	192	12.79	114	15.30	177	16.50	163
21.16	340	20.17	244	23.95	310	25.82	316
51.9	569	27.27	331	47.5	426	54.9	468
127.0	777	52.0	460	75.9	518	126.8	611
225.7	896	82.6	564	203.1	701	249.0	722
307.2	955	185.1	716	318	784	333	766
422	1015	313	820	436	841	450	813
		429	882				

t=327°C		t=418°C		t=497°C		t=634°C	
H	I	H	I	H	I	H	I
8.01	38	6.45	41	23.6	5.9	83	2.5
16.46	167	13.19	111	52.4	14.6	214	6.9
25.33	298	22.50	193	97.1	28.4	239	10.2
59.9	461	33.6	256	158.9	42.6	507	12.6
109.9	556	68.5	352	364	79.4		
224.1	659	117.3	428	506	93.9		
365	726	266.7	527				
443	752	446	584				

t=795°C		*t*=399°C		*t*=101°C		*t*=24.2°C	
H	I	H	I	H	I	H	I
60	2.1	98	4.2	24	1.1	0.10	41
157	5.2	262	9.7	107	6.6	3.85	207
342	9.6	511	14.3	258	14.6	23.07	285
511	12.0			507	24.2	96.1	303
						257.5	319
						490	334

NICKEL STEEL 28.32%.

t=12.5°C		*t*=130°C		*t*=300°C		*t*=453°C	
H	I	H	I	H	I	H	I
3.28	21	5.16	26	7.43	33	12.45	28
6.67	75	9.36	77	17.01	156	28.82	72
14.58	183	17.05	233	25.74	293	45.6	114
24.56	328	25.68	348	47.2	434	89.1	185
41.4	438	40.8	432	95.6	582	189.2	287
65.6	555	81.7	579	194.3	697	314	339
132.1	713	183.5	734	318	778	469	401
266.6	861	315	833	439	824		
420	962	423	872				

t=504°C		*t*=649°C		*t*=818°C		*t*=581°C	
H	I	H	I	H	I	H	I
22	1.4	114	4.5	120	3.9	109	3.9
52	3.9	217	7.2	263	7.9	246	7.9
276	24.3	516	12.5	513	11.4	385	10.8
506	39.5					510	13.7

t=387°C		*t*=200°C		52°C		12.8°C	
H	I	H	I	H	I	H	I
105	4.8	105	5.1	46	3.7	3.19	20
216	8.2	215	9.1	111	8.4	18.38	36
367	11.7	341	12.5	388	23.1	37.8	46
512	14.2	511	15.9	513	28.8	125.2	72
						289	102
						492	126

NICKEL STEEL 26.64%.

t=15.3°C		*t*=121°C		*t*=239°C		*t*=392°C	
H	I	H	I	H	I	H	I
2.55	10	5.20	25	6.38	27	5.03	55
10.22	65	9.02	59	13.88	93	9.42	138
16.87	154	16.46	163	19.21	209	13.93	226
25.32	292	24.45	297	26.04	341	24.14	364
37.4	402	33.2	384	39.1	482	60.6	553
57.4	581	50.2	533	54.1	613	111.9	665
105.3	737	104.9	738	100.9	755	226.4	774
180.1	876	179.4	867	192.3	882	420	849
271.1	976	290	969	330	982		
406	1064	401	1035	395	1001		

t=463°C		*t*=517°C		*t*=665°C		*t*=828°C	
H	I	H	I	H	I	H	I
7.27	28	50	2.4	104	3.9	79	3.5
15.03	63	204	10.3	248	8.8	301	9.8
28.18	121	484	20.2	484	13.9	481	13.6
40.5	167						
101.1	297						
216.1	417						
352	480						
439	538						

$t=514°C$		$t=401°C$		$t=227°C$		$t=80°C$	
H	I	H	I	H	I	H	I
103	4.5	123	5.4	124	5.2	113	5.6
301	10.3	303	10.8	301	10.5	301	12.4
480	14.4	479	14.8	480	15.0	479	16.6

NICKEL STEEL 24.40%.

$t=13.0°C$		$t=101°C$		$t=190°C$		$t=366°C$	
H	I	H	I	H	I	H	I
3.89	14	8.42	37	12.11	71	9.00	58
12.35	66	19.06	155	19.50	184	16.20	187
20.60	171	27.62	282	27.16	304	23.75	331
27.75	297	48.4	450	49.5	508	40.5	475
56.09	497	81.7	618	61.3	579	62.9	589
126.5	744	152.4	775	148.3	791	132.0	733
184.9	837	229.5	864	261.2	903	213.3	805
296	941	308	926	420	988	312.0	856
400	1009	419	991			427	895

$t=466°C$		$t=490°C$		$t=392°C$		$t=207°C$	
H	I	H	I	H	I	H	I
5.25	35	8.48	25	12.42	30	10.39	37
10.72	89	18.47	60	15.66	73	23.25	96
25.72	234	39.2	138	40.5	125	37.78	167
44.7	338	73.2	226	80.3	230	76.7	302
113.7	521	145.4	343	165.8	362	138.5	438
244.9	645	296	456	279.4	460	272.2	575
442	724	458	516	455	542	447	661

t=14.2°C		t=237°C		t=410°C		t=490°C	
H	I	H	I	H	I	H	I
5.78	32	8.17	28	12.55	33	14.36	29
13.39	86	16.48	61	23.55	68	37.3	90
20.82	155	31.36	126	38.2	126	90.4	209
47.2	375	74.9	267	73.2	201	184.1	327
77.0	543	155.6	425	105.2	270	342	423
164.8	722	309	569	230.6	413	434	465
260.0	797	449	631	334	489		
412	880			447	538		

t=542°C		t=591°C		t=851°C		t=1000°C	
H	I	H	I	H	I	H	I
29.2	13	56.7	2.0	57.1	1.7	105	2.5
98.8	50	166.5	5.2	152.0	4.1	305	6.0
338	128	308.2	8.2	308.3	7.4	483	7.3
472	146	483	10.5	486	8.7		

t=1200°C		t=861°C		t=212°C		t=14.6°C	
H	I	H	I	H	I	H	I
290	3.4	105.3	2.1	64.4	5.1	19.6	25
448	3.6	304	4.7	165.4	8.9	46.2	83
480	3.7	481	5.4	323	11.9	92.8	124
				485	13.8	193.6	176
						351	214
						464	233

NICKEL STEEL 24.04%.

$t=10.1$°C		$t=182$°C		$t=287$°C		$t=452$°C	
H	I	H	I	H	I	H	I
2.44	6	3.68	13	3.48	14	3.81	27
10.74	42	11.43	54	12.36	77	12.27	123
27.60	230	20.48	138	18.63	193	24.91	254
35.6	306	26.97	270	23.06	313	47.7	372
58.2	520	39.1	386	33.2	427	71.9	452
80.6	641	58.9	552	51.8	592	164.3	602
115.0	756	90.7	703	95.7	760	271.2	673
185.6	888	174.7	875	183.4	886	447	745
276.2	985	284.5	982	275.8	954		
393	1060	395	1046	383	1002		

$t=531$°C		$t=586$°C		$t=717$°C		$t=604$°C	
H	I	H	I	H	I	H	I
41	1.9	101	3.4	124	4.6	64	3.4
184	7.9	268	7.7	348	10.0	236	7.7
370	13.7	487	11.5	487	12.1	411	11.3
490	16.2					489	12.9

$t=502$°C		$t=274$°C		$t=193$°C		$t=11.3$°C	
H	I	H	I	H	I	H	I
79	3.0	50	2.8	34	1.8	57	2.8
250	9.0	151	7.7	102	5.7	165	8.9
392	11.9	352	14.1	310	12.9	286	13.8
487	13.8	487	16.6	494	16.5	484	18.9

From these values, the curves of magnetization to temperature are obtained and drawn in Fig. 7 e, f, g, h, i, j, k. In these figures, we have included the results obtained in the first and second experiments.

Here we also notice that except with 28.74%, the magnetizability of these alloys had considerably changed by the heating and cooling, which the alloys underwent since the first experiment. Hence in some of the figures, the portions corresponding to the first experiment were displaced parallel to themselves so as to form closed curves. Thus the displaced portions are given in dotted lines.

As the temperature gradually rises from −186°C, the magnetization of 29.24% Ni diminishes at first slowly, then rapidly, and after passing through an inflexion point, the diminution becomes slow. The curve, passing through a second inflexion point, begins to descend very rapidly, as the critical temperature is approached. If this temperature be passed, the diminution of the magnetization by heating is very small, so that the curve is nearly parallel to the axis of temperature. From the course of the curve, it seems probable that the magnetization does not altogether vanish, till the melting point of the specimen is reached. As the temperature is next gradually reduced, the increase of magnetization is very small; this state continues, till the temperature falls to about 100°C; then the increase becomes very rapid. For example, in H=400 C.G.S., the intensity of magnetization at the descending temperature is only 20 C.G.S. for a temperature of 80°C, but it amounts to 200 for 20°C, and at −60°C, it increases to 790. Thus the magnetization of the specimen displays a remarkable difference between the ascending and descending branches of the curve.

The above manner, in which the magnetization is changed by temperature, is common to all other irreversible nickel steels. As the percentage of nickel decreases, the concave portion of the ascending branch becomes fainter and fainter; and with 24.40% and 24.04% Ni, it almost vanishes for strong fields. Apparently, the forms of the two curves for nickel steels of 29.24% and 24.04% Ni, are widely different from each other; but if we compare the forms of the curves of two consecutive nickel steels, we can trace transition stages from one form to the another.

The critical temperatures of the alloys for H=400 C.G.S. are given in the following table:—

Alloys	29.24%	29%	28.74%	28.32%	26.64%	24.40%	24.04%
Ascending branch	530°C	530°C	530°C	510°C	510°C	580°C	520°C
Descending branch	70	140	80	50	10	130	40

Thus in the ascending branch, the critical temperatures of these irreversible nickel steels are nearly equal, except with the last but one. The above numbers fairly coincide with those obtained by M. OSMOND, except with 24.40% Ni. With this alloy, the critical temperatures are greater, in our case, by about 50°C for the ascending branch and 100°C for the descending, than in the experiment by OSMOND. The values given by L. DUMAS for the first four of these alloys are considerably less than those obtained by us; but for the remaining alloys, the contrary is the case. These discrepancies may probably be due to the previous history of the alloys.

It remains to mention a singular phenomenon. If at a point in an ascending branch of the temperature-cycle, the temperature be reduced to the ordinary, the path is utterly different from the ascending one. If, however, the temperature be again increased to its former value, the path nearly coincides with the former one; the further increase of temperature diminishes the magnetization in such a manner that the magnetization is not interrupted by the cooling process. An instance is seen in Fig. 7 j. Hence in irreversible nickel steels, the magnetization at ordinary temperature can have *any value whatever* within a given limits, if the cooled specimens be heated to a suitable temperature. Becquerel who first studied the magnetic properties of irreversible nickel steels, found that in the alloy, there were two states of stable equilibrium; but according to our results, there are an infinite number of such states, a fact which may possibly prove to be important in the theory of molecular magnetism.

Comparing the magnetization at different temperatures in these nickel steels, we notice that the critical temperature in the descending branch of the temperature-cycle generally becomes less, as the percentages of nickel decreases. As the content of nickel diminishes from 70.32% to 26.64%, the critical temperature falls from several hundred degrees to the ordinary temperature. It is then highly probable that 25% nickel steel, which is feebly magnetic both at ordinary and liquid air temperatures, would become strongly magnetic, if the cooling should be pushed still further. If it once become strongly magnetic by cooling, it may preserve this property, after the alloy is heated to the ordinary temperature. It will be interesting to investigate, whether other non-magnetic alloys, which consist of a magnetic and a non-magnetic metal, would display a similar phenomenon on being cooled to a sufficiently low temperature.

The fact that the two strongly magnetic metals form a non-magnetic metal is then nothing more than the lowering of the critical temperature of the alloy to the ordinary temperature. Owing to some changes occuring in the molecular configuration during the process of fusion of the constituent metals, the critical temperature of the alloy in the descending branch of the temperature-cycle falls to a low temperature, and therefore the alloy behaves as a weakly magnetic or non-magnetic alloy at ordinary temperature. The same remark will also apply to a non-magnetic alloy which consists of a magnetic metal and a non-magnetic ones. The above view is also favored by the fact that in irreversible alloys, the hysteresis-loss at ordinary temperature is markedly small, which corresponds to the hysteresis of iron or nickel at high temperatures, but its value at a low temperature considerably increases, corresponding to the hysteresis of the same metal at ordinary temperature.

Fig. 1. a.

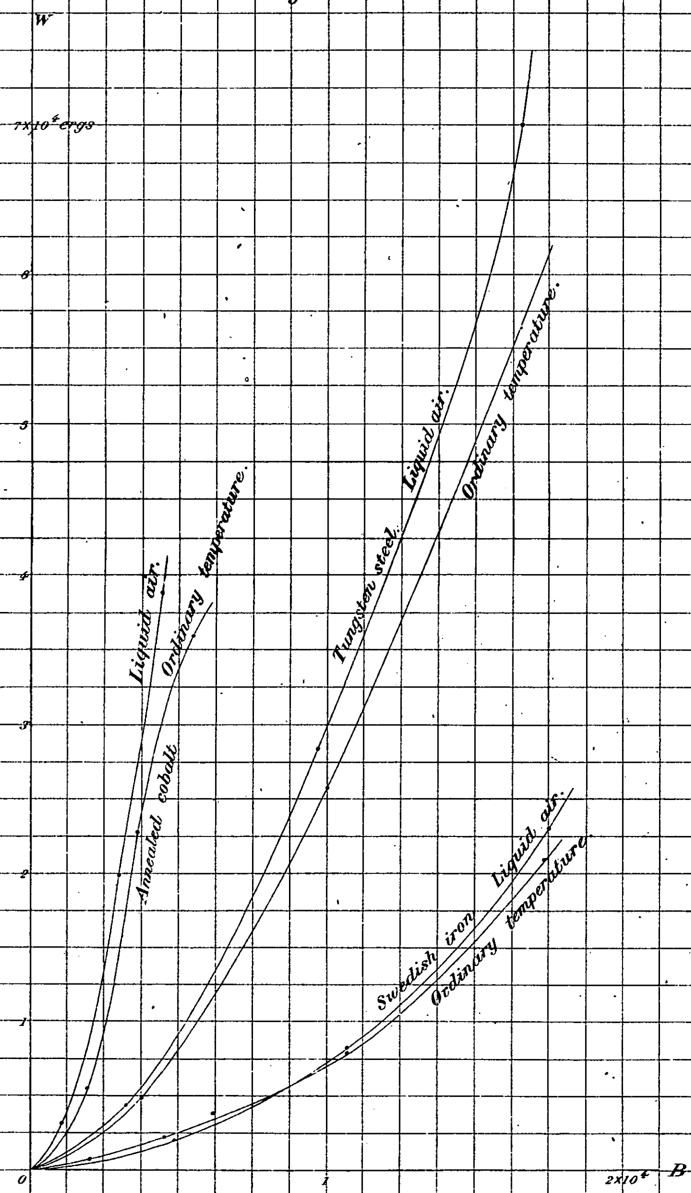


Fig. 1. b.

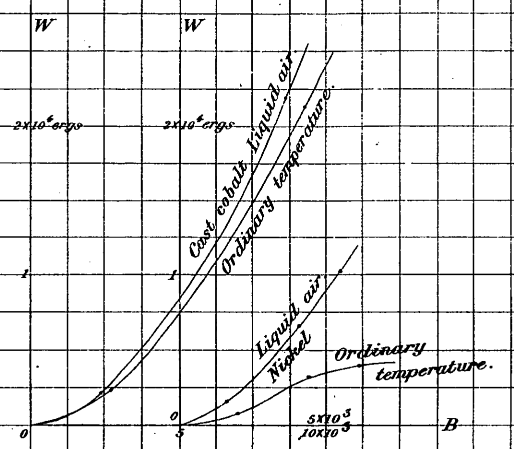


Fig. 2, a. Nickel steels.

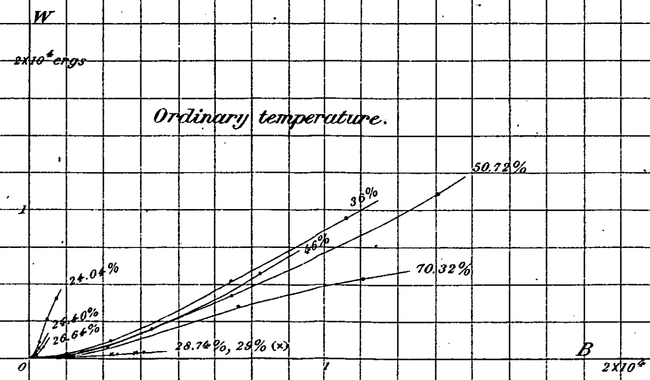


Fig. 2, b. Nickel steels.

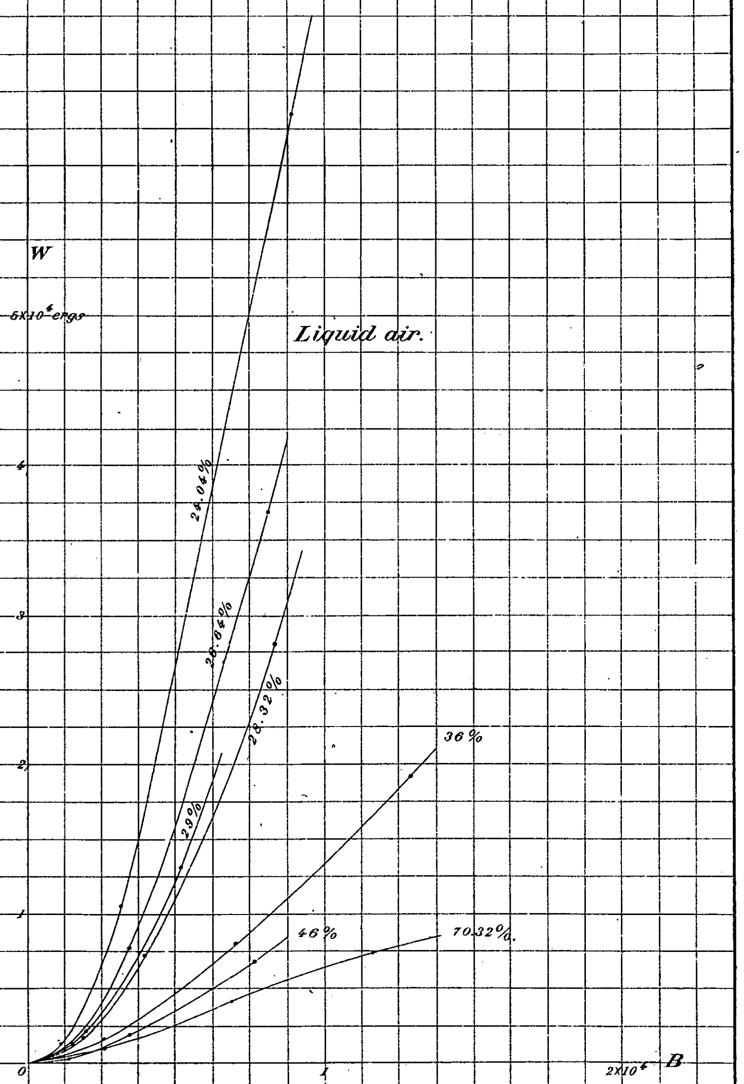


Fig. 3, a.

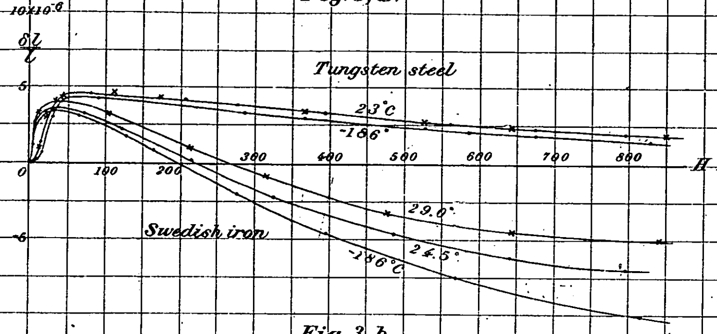


Fig. 3, b.

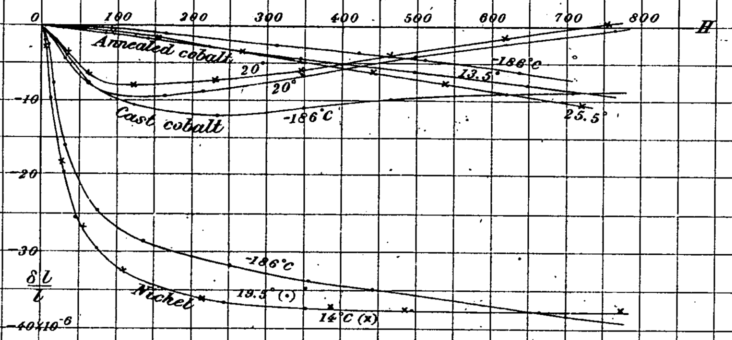


Fig. 4, a; 70.32%, 50.72% Ni.

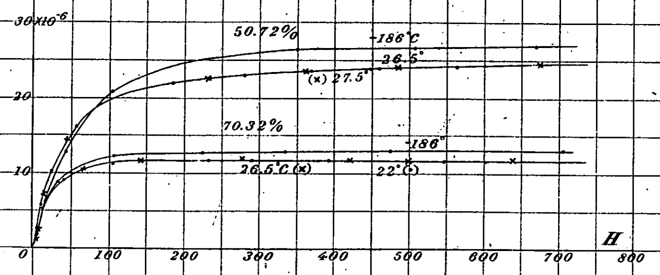


Fig. 4, b; 36% Ni.

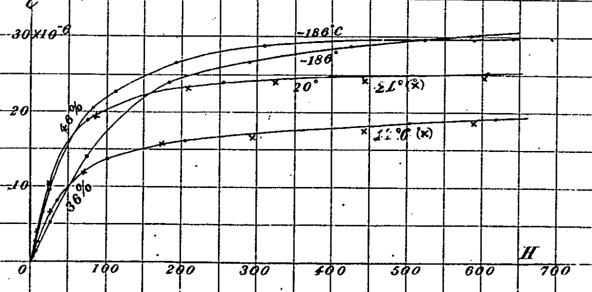


Fig. 4, c; 29.24% Ni.

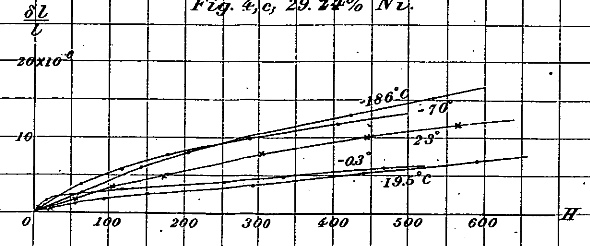


Fig. 4, d; 29.% Ni.

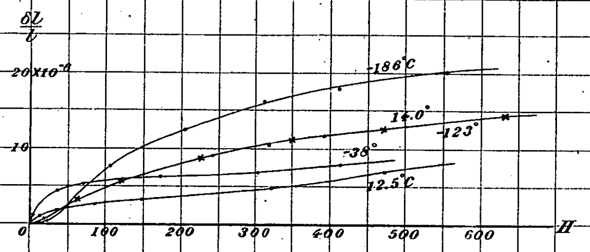


Fig. 4, e; 28.74% Ni.

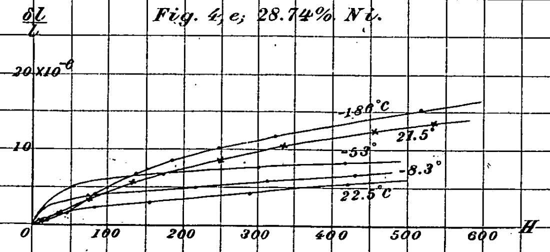


Fig. 4, f; 28.32% Ni.

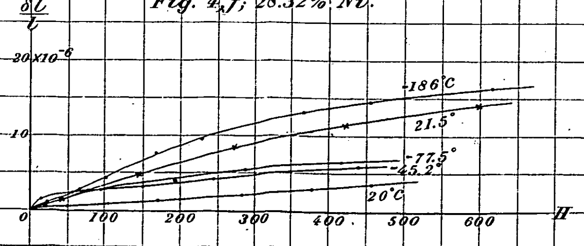


Fig. 4, g; 26.64% Ni.

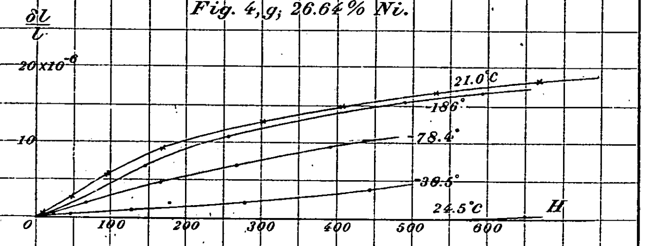


Fig. 4, h; 24.40% Ni.

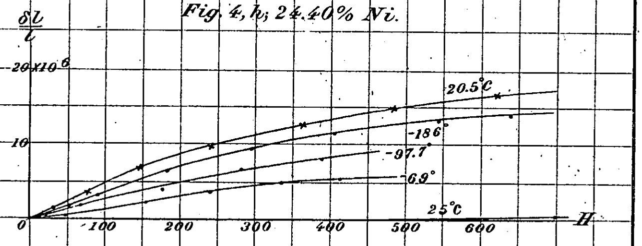
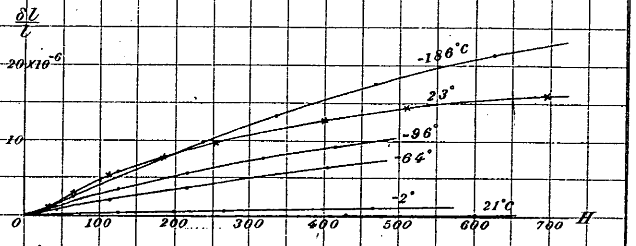


Fig. 4, i; 24.04% Ni.



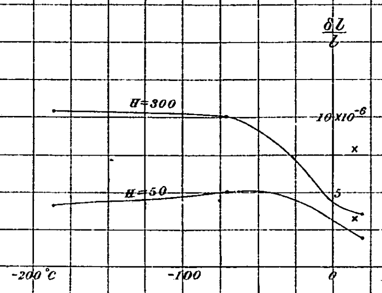


Fig. 5, a; 29.24% Ni.

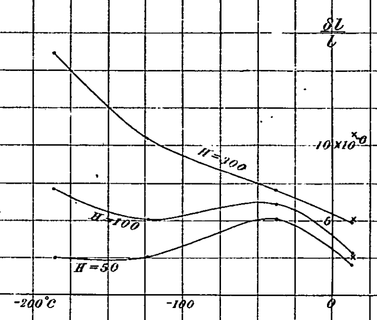


Fig. 5, b; 29% Ni.

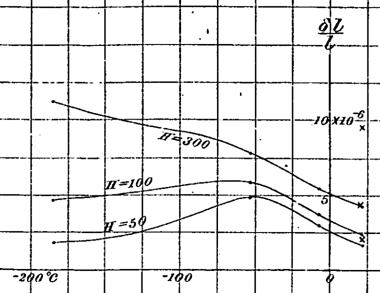


Fig. 5, c; 28.74% Ni.

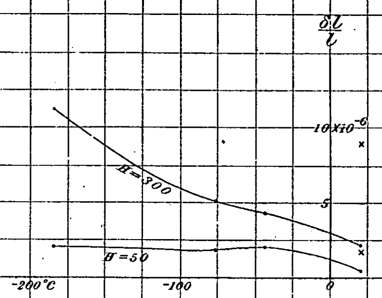


Fig. 5, d; 28.32% Ni.

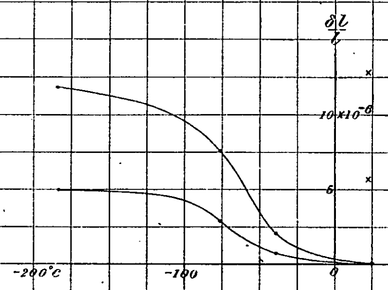


Fig. 5, e; 26.64% Ni.

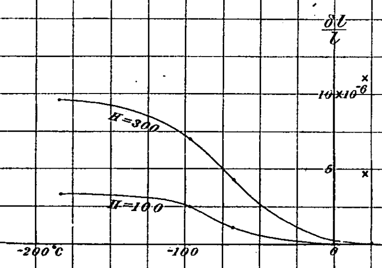


Fig. 5, f; 24.40% Ni.

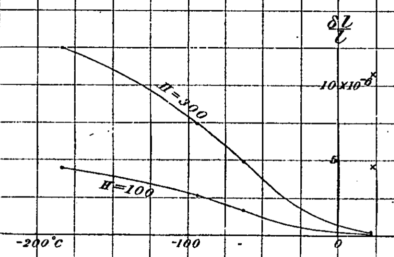


Fig. 5, g; 24.04% Ni.

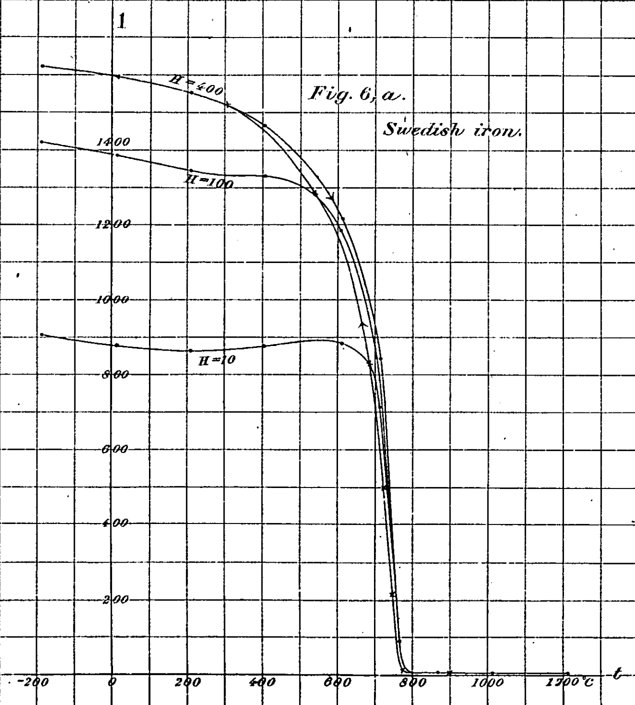


Fig. 6, a.

Swedish iron.

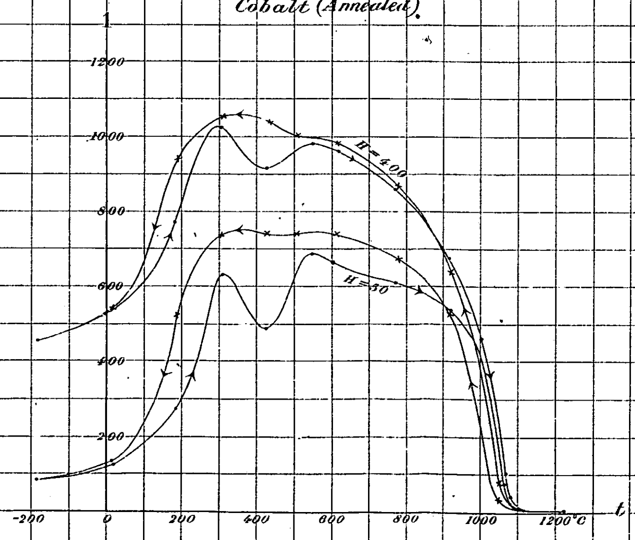


Fig. 6, b.

Cobalt (Annealed).

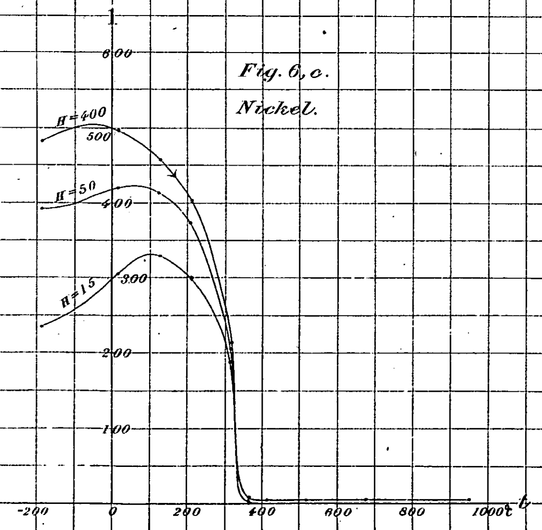


Fig. 6, c.

Nickel.

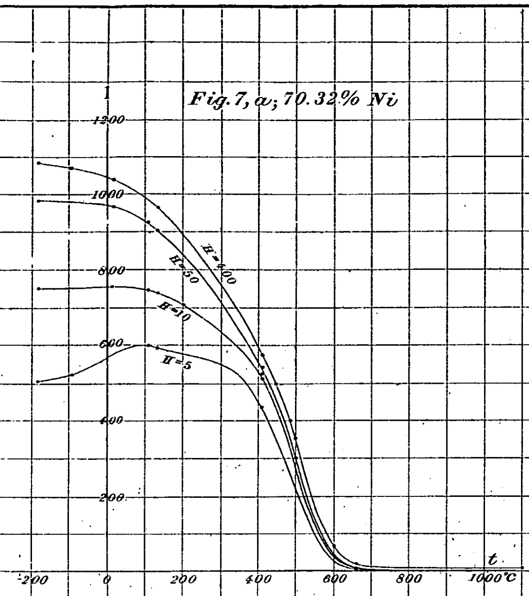


Fig. 7, a; 70.32% Ni

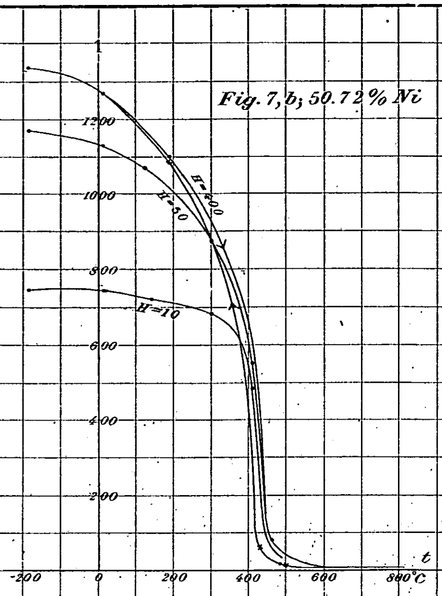


Fig. 7, b; 50.72% Ni

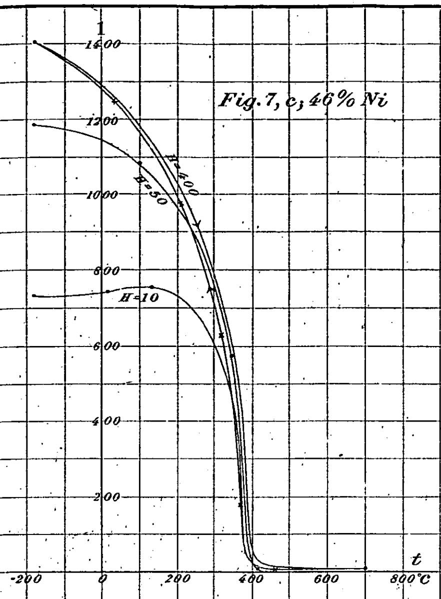


Fig. 7, c; 46% Ni

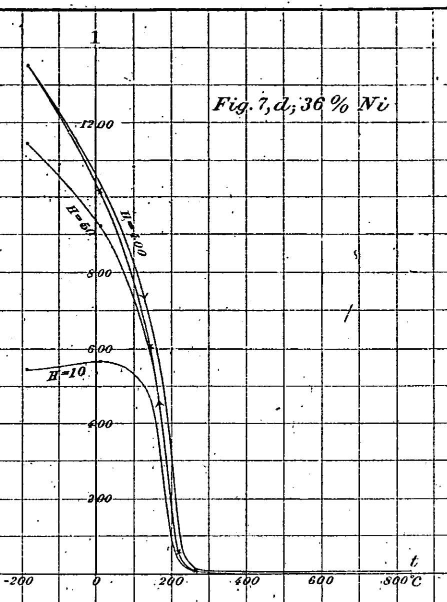


Fig. 7, d; 36% Ni

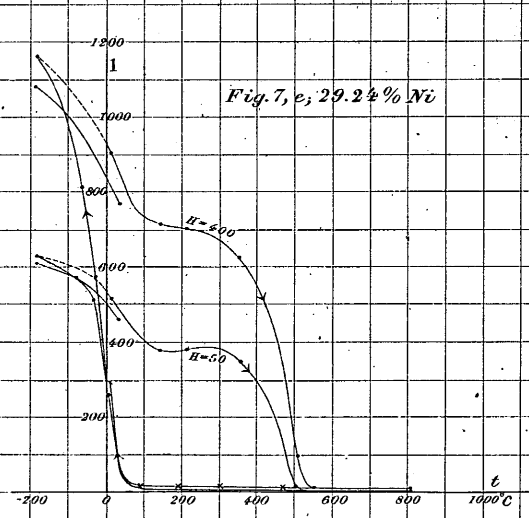


Fig. 7, e; 29.24% Ni

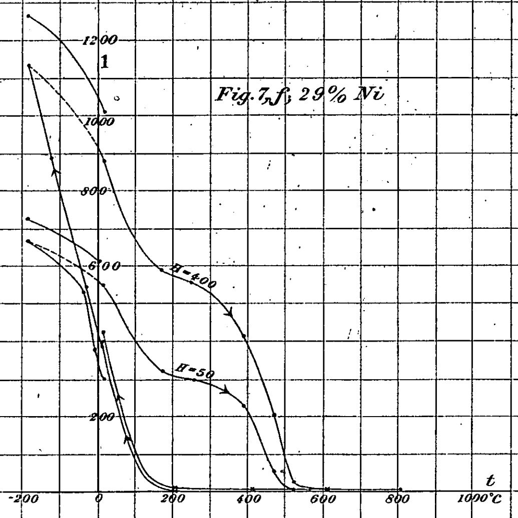


Fig. 7, f; 29% Ni

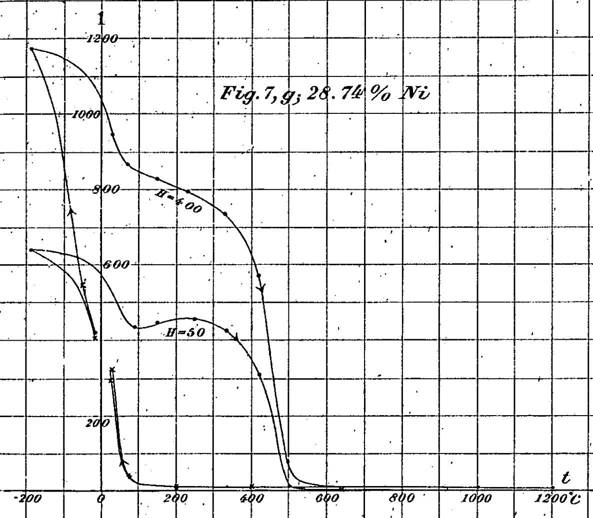


Fig. 7, g; 28.74% Ni

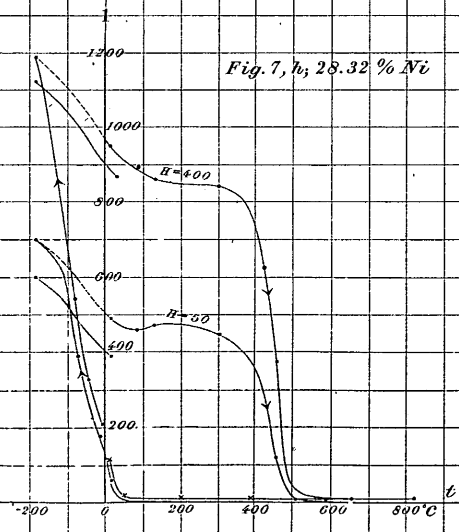


Fig. 7, h; 28.32% Ni

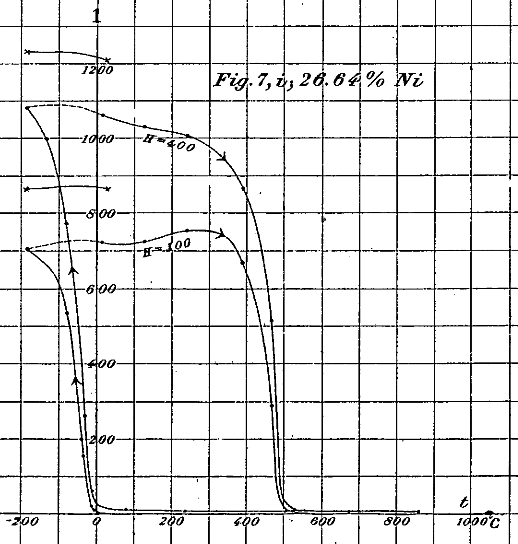


Fig. 7, i; 26.64% Ni

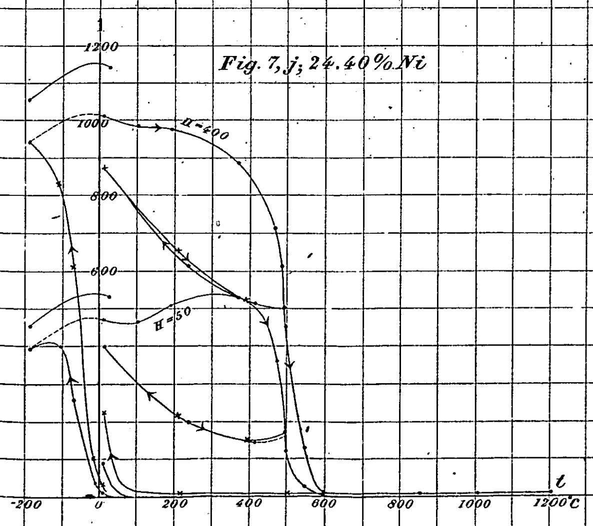


Fig. 7, j; 24.40% Ni

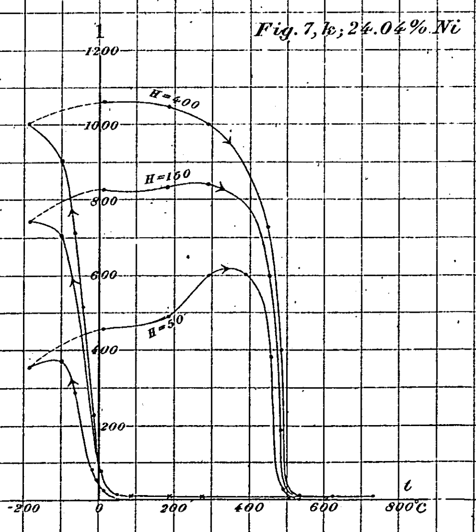


Fig. 7, k; 24.04% Ni