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Change of Length of Ferromagnetic Substances under High and Low Temperatures by Magnetization.

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With Plates I—III.

The interesting experiments of Hopkinson on magnetization at high temperatures promise us some important results in the magnetic change of length at such temperatures. On account, however, of the experimental difficulties, this interesting subject has as yet scarcely been investigated. Barrett[*] was the first to touch the subject ; with a rise of temperature of about 50°C, he observed no effect on the magnetic change of length in iron and cobalt ; but in nickel, the contraction was reduced to about two-thirds of its ordinary value. A few years ago, one of us[†] studied the same effect in iron, tungsten steel, and nickel at temperatures ranging from 18°C to 100 C. In weak fields, the magnetic elongation of iron was slightly diminished by heating ; but in strong fields, it was increased. In tungsten steel, the elongation was always diminished ; in nickel, the contraction was considerably reduced except in weak fields, in which a minute increase of contraction was sometimes observed.

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[*] Barrett, Phil. Mag. [4] **47**, 51, 1874 ; Nature **26**, 515, 586, 1882 ; Beibl. **7**, 201.

[†] K. Honda, Jour. Sc. Coll. XIII, 83, 1900.

In these experiments, the range of temperatures was very limited, so that the remarkable effect of high temperatures was not observed. In the present case, the experiments were pushed beyond the critical temperature of iron ; in addition to this, the change of length in liquid air was also examined.

§ 1. APPARATUS.

The apparatus for measuring the change of length by magnetization at high and low temperatures was substantially the same as that used for the study of the effect of tension on the magnetic change of length.* Repeated experiments showed that this arrangement gave very consistent results, but that it was rather preferable to flatten the surface of the vertically suspended wire in contact with the rotating cylinder. To diminish the effect of tension on the magnetic change of length as well as the yielding at high temperatures due to tension, thick rods about 1 cm in diameter and 21 cm in length were employed. In the experiments at high temperatures, the suspended weight was generally 1 or 2 Kilograms ; its effects were consequently almost insensible. To the upper end of the ferromagnetic rod, a copper rod about 1 cm thick and 25 cm long was jointed by means of a copper screw, and then brazed. The lower end of the rod was likewise attached to a similar copper rod about 20 cm long. The screwed part in each end of the ferromagnetic rod was 1.5 mm. This connected system hung vertically from a stout support by means of a brass stand with three levelling screws. The support on which the tripod stand rested, was provided with a brass plate with a hole-slot-plane arrangement. The free end of the bar was connected with a copper wire about 1.5 mm thick

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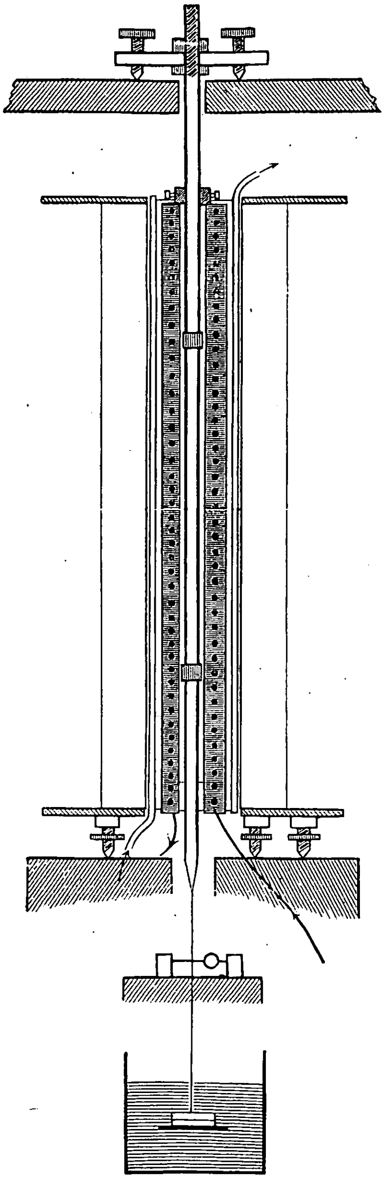
* K. Honda and S. Shimizu, Jour. Sc. Coll. XVI, Art. 9, 1902; Phil. Mag. 4, 338, 1902.

which was stretched by a weight dipping in a vessel of water.

Heating was effected by means of an electric current. The heating coil was wound on a copper tube 40 cm long and 2.5 cm in diameter well insulated with asbestos paper. The coil was wound anti-inductively two turns per centimeter by a wire about 1 mm thick. Two heating coils of the same dimensions were prepared, the one wound with a German silver wire and the other with a nickel wire. The former coil was used in the experiments below 700°C and the latter for higher temperatures. The melting point of nickel is about 1500°C, while its magnetic property is lost at a temperature below 400°C; hence above this temperature, the presence of the metal does not at all disturbe the magnetic field. By using a nickel wire for experiments at high temperature, we may dispense with a costly platinum wire or foil.



The heating coil was fixed by screws to the upper copper rod; while in its lower end was a hole, through which the lower copper rod passed without being in contact. The air current which might enter or escape through this narrow opening was diminished on one side by another partition placed 5 cm above the lower end of the coil, and on the other side, by a bundle of fibrous asbestos attached to the copper rod just below the same end.

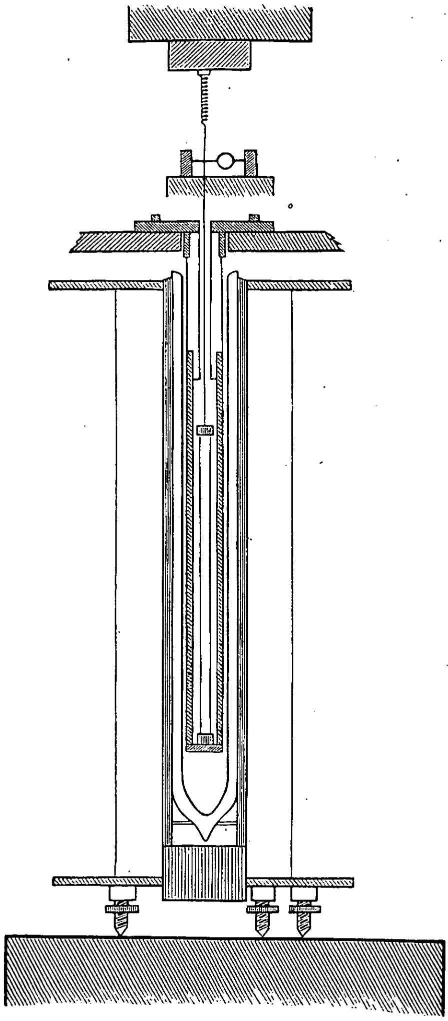
The exposed parts of the copper rods and wire were well covered with asbestos paper, except the part where the wire came in contact with the rotating cylinder. This precaution was necessary to diminish the loss of heat, and also to avoid the oscillating displacement of the image in the field of the telescope due to thermal expansion and contraction caused by the air current.

The temperature of the samples to be tested was measured by means of a platinum rhodium-platinum junction which was loosely placed in contact with the sample at its middle part, while the rest was insulated with asbestos paper. The other junction, also well insulated, was inserted into a copper tube dipped in a water bath of the temperature of the room. The thermoelectric current in the circuit was measured by a d'Arsonval galvanometer, and the constant of the pyrometer was determined by means of a mercury thermometer below 300°C, and by the melting points of zinc and sodium chloride above that temperature.

A magnetizing coil with a water-jacketed arrangement was placed co-axially with the suspended rod ; it was 40 cm long and gave a field of 39.44 C.G.S. units at the center due to a current of one ampere.

When the adjustment was finished, the exposed parts were well covered with fibrous asbestos and cotton in order to diminish the loss of heat, care being taken to produce no sensible resistance to the elongation or contraction of our specimens.

For the measurement of the magnetic change of length in liquid air, the above arrangement was modified in the following way. The specimen was stretched upwards by means of a spiral spring,



instead of stretching it by a suspended weight. The shaded portions of the protruding holder were made of brass, while the unshaded part was made of wood to lessen the conduction of heat. Care was specially taken to stretch the copper wire in the direction of the axis of the rod.

The magnetizing coil with a Dewar's tube inside it, was placed co-axially with our rod. The contraction or elongation of the specimen was measured by the rotating cylinder in contact with a vertical copper wire. The temperature of liquid air was assumed to be −186°C.

§ 2. METHOD OF OBSERVATION.

The experiments at low temperature were conducted in the following manner. The change of length at the temperature of the room was first determined and compared with the corresponding result obtained by the heating arrangement. The comparison showed that these two results nearly coincided with each other. The liquid air was then gently poured into the Dewar's tube, until this tube was filled with the liquid, and the exposed parts above the magnetizing coil were carefully protected with cotton.

Owing to the boiling of the liquid, a small oscillation of the image in the field of the telescope was first observed ; but after about 10 minutes, the image became somewhat steady. The magnetic change of length was then measured in the usual way.

The experiment at high temperatures were undertaken in the following order. The magnetic change of length at the temperature of the room was first determined. Then an electric current from a dynamo was passed through the heating coil for one or two hours, till the temperature of the core became nearly constant ; then the current from the dynamo was replaced by one from an accumulator in order to get rid of the fluctuation of temperature due to that of the dynamo-current. Twenty or thirty minutes passed before the observations were taken, when the temperature had become very steady. The change of temperature caused a deflection of more than 6 cm per degree in the field of the observing telescope, whereas the deflection due to magnetization was utmost 5 cm in nickel and 1.5 cm in soft iron ; hence it can be easily conjectured how great difficulty is experienced in obtaining a constant temperature. Since the demagnetization was carefully effected before each observation and then an instantaneous deflection was noted, a slow displacement of the image, such as 1 mm in several minutes, could not cause any sensible error in the results. In our experiments, during the whole set of observations which usually required 10 or 15 minutes, the displacement of the zero point was only 2 or 3 mm except in a few cases.

If one set of observations was taken, a current of increased strength was again supplied by the dynamo for about an hour or more, till, the temperature became nearly constant. The current-supply from the dynamo was then changed for that from the accumulator to repeat the same subsequent processes. In this way, experiments at successively increasing temperatures from the ordinary to the highest were carried out. Our heating coil gave a rise of temperature of about 1000°C in the core by passing a current of 11 amperes.

When the specimen was once heated to a high temperature, it underwent a permanent change with regard to the magnetic change of length; thus it was necessary to try the experiment at low temperatures before our specimens had been heated to high temperatures.

The sensibility of our apparatus was such that an elongation or contraction of 5×10^{-8} of our specimens could easily be observed.

We tested 6 different samples shown in the following table :—

Metals	Length	Diameter	Demagnetizing factor
Soft iron	22.05 cm	1.025 cm	0.0683
Tungsten steel (rod)	22.93	0.940	0.0562
,, ,, (prism)	22.00	0.948 × 0.953	0.0751
Cast cobalt	22.10	1.044	0.0722
Ann. cobalt	22.03	1.083	0.0758
Nickel	22.03	1.121	0.0801

§ 3. RESULTS OF EXPERIMENTS.

The change of length of our specimen at the temperature of the room (8°C--17°C) is shown in Fig. 1.

The full lines represent the curves of the change of length plotted against the internal field ($H' = H - IN$); the dotted lines refer to the external field. The comparison of the corresponding curves shows us the influence of the demagnetizing force.

In experiments at high temperatures, the internal field for a given magnetizing current varies with the temperature, as the intensity of magnetization changes with it. A full knowledge of the field in which experiments were carried on requires the determination of the intensity of magnetization at each temperature and field. Since our experiments did not extend so far, the curves of the length change at different temperatures were drawn for the external field. But if we refer to Fig. 1, it is easy to see how the forms of these curves are to be changed, if the effective field be used instead of the external one.

Nickel. The change of length in nickel under high and low temperatures is graphically shown in Fig. 2. The rise of temperature markedly reduces the magnetic contraction of the metal. At a temperature of 240°C, the contraction in $H=800$ is already reduced to half its ordinary value, and at 400°C, it almost vanishes. With the ovoid of the same specimen, Professor H. Nagaoka and Mr. S. Kusakabe found the critical temperature to be 400°C. In liquid air, the contraction is reduced in weak fields, but is increased in strong fields. The relation between the change of length and the temperature for given external fields is given in Fig. 3. Each curve has a minimum point, the temperature of which decreases as the field is increased.

We also notice that the contraction vanishes asymptotically, as the temperature approaches to 400°C. It is to be remembered that on account of the demagnetizing force, each curve does not represent the contraction in a constant effective field, but shows the general feature of contraction with regard to temperature. The former results are consistent with the corresponding results in the present experiment.

Soft iron. The change of length in soft iron is given in Fig. 4. As the temperature is raised, the contraction in high fields gradually disappears and at 312°C, the change of length is similar to that of tungsten steel at ordinary temperatures. With further increase of temperature, the elongation, after passing a maximum, gradually decreases. We could trace the elongation up to 970°C, which is far higher than its critical temperature. The effect of cooling by liquid air is considerably large in strong fields, producing an increase of contraction.

The relation between the change of length and the temperature is given in Fig. 5. It is remarkable to observe that the maximum elongation in weak fields which is characteristic for iron, remains almost constant for the temperatures ranging from −186°C to 200°C. Above this temperature, the elongation increases, till it reaches a maximum, and then rapidly decreases.

Tungsten steel. The results of experiments in tungsten steel are given in Figs. 6 and 7. The course of the curves and its change with temperature are similar to those of soft iron at temperatures higher than 500°C. The change of length seems to disappear nearly at the critical temperature, namely 900°C, a value obtained by Professor H. Nagaoka and Mr. S. Kusakabe. The former result obtained by one of us approximately agrees with the corresponding result in the present experiment.

With tungsten steel, we first studied the effect of temperature ; when the specimen was cooled down to its initial temperature, it underwent a considerable permanent change with regard to the change of length. So the experiment in liquid air was performed with another rod of square section cut from the same specimen as the cylinder. The curves for 10°C and −186°C are given in Fig. 8 which shows a slight effect of cooling on the change of length. Cooling decreases the elongation of the alloy in weak fields, but increases it in strong fields.

Cast cobalt. The results of observation in cast cobalt are drawn in Fig. 9. As the temperature is raised, the magnetic contraction in weak fields gradually lessens, and the elongation in strong fields increases, till it reaches a maximum. At temperatures higher than 800°C, the initial contraction altogether disappears and the course of the curves resembles that of iron and steel at high temperatures. If the temperatures be further increased, the elongation diminishes steadily, but at a diminishing rate, and even at such a high temperature as 1020°C, we still observe a considerable elongation of the metal. From the course of the curves in Fig. 10, it is easy to see that in $H=800$, the elongation does not vanish up to a temperature of 1200°C, which is higher than its critical temperature by 100°C. With our arrangement, it was not possible to push the experiments still further, as the melting point of copper was not far from that temperature. It is also to be observed that the field of maximum contraction gradually decreases as the temperature is raised, and that the temperature of maximum elongation in a given field diminishes as the field is increased.

With the same specimen, the effect of high temperature was first studied, and when the specimen was cooled down to its initial temperature, it totally changed its character with regard to the magnetic change of length. It was therefore not possible to examine the effect of cooling of the metal in the cast state.

Annealed cobalt. The specimen was annealed in a charcoal fire for about 4 hours, being carefully wrapped in asbestos papers. The effect of high temperatures on the magnetic change of length in annealed cobalt presents an extraordinary feature, as may be seen from Fig. 11. As the temperature is raised, beginning with that of liquid air, the contraction increases at first slowly and then rapidly, till it reaches a maximum. It then decreases and after passing the state of no contraction, it is changed to an elongation, which again increases with the temperature up to a maximum, and then gradually diminishes. At such a high temperature as 1034°C, we could still observe a considerable elongation of the metal. To judge from the course of the curves, the temperature at which the elongation at last vanishes is nearly the same as in the cast cobalt. It is interesting to observe that the curve of the length change at a temperature near 450°C is similar to that of iron at ordinary temperature. The cobalt slightly elongates in weak fields ; but it contracts in strong fields. At a temperature higher than 500°C, the cast and annealed cobalts resemble each other in their behaviour in respect of the change of length.

The curves (Fig. 12) showing the relation between the change of length and the temperature, present a peculiar feature. They have generally a maximum point and a minimum ; in low fields, however, two small maxima and minima are observed. They also pass through a point (464°C) in the axis of the temperature. It follows then that there is a certain temperature, at which the change of length in the annealed cobalt nearly disappears for all magnetizing fields, and that the change occurs in an opposite sense in every field, according as the specimen is heated above or below that temperature. It appears then that annealed cobalt undergoes some molecular change at that temperature.

General remarks. On comparing the above results in soft iron, tungsten steel, cast and annealed cobalts, we notice the remarkable fact that the changes of length of these metals, at ordinary temperature so very different from each other, assume, at sufficiently high temperatures, an extraordinarily simple character ; they tend to become proportional to the magnetic force, a fact which has no doubt an important bearing in the theory of molecular magnetism. In Fig.

13, curves are drawn, one for each specimen, for the elongations at such temperatures that each specimen produces the same elongation in $H=500$. They all run very close to each other. It is also to be observed that the change of length at the critical temperature nearly disappears, and even in cases, in which we actually observe it, the amount of the change is a small fraction of that observed at ordinary temperatures.

In conclusion, let us give a short account of the permanent change with regard to the magnetic change of length. Cooling the specimens by liquid air generally produces no permanent effect on the length change at ordinary temperature; but heating it to a very high temperature produces a considerable permanent change. As seen from Fig. 14, the heating of annealed soft iron up to 746°C does not sensibly affect the change of length at ordinary temperature. Here the cross (×) denotes the points obtained after heating to 746°C. In tungsten steel, the effect is very large, tending to reduce the elongation in high fields (Fig. 15). In cast cobalt, the effect is still greater, changing totally the course of the curve, as seen from Fig. 16. If the specimen is once annealed at a high temperature, the subsequent heating and cooling between the same range of temperatures almost produce no effect on the change of length at ordinary temperature. But if the upper range of temperature be further increased, the change of length is slightly affected. This will be seen from the example of annealed cobalt (Fig. 17).

In the experiments at temperatures higher than 700°C, the suspended weight was reduced to 1 or 0.4 kilogram, according to circumstances. This was found necessary to avoid the gradual elongation of our specimens caused by the yielding at high temperatures.

It is hoped that the present investigation may be completed by studying the change of length in every stage of rising and falling temperatures, and also by measuring the magnetization at the corresponding temperatures. The further extension to other ferromagnetics, such as nickel steels of different percentages, will also be undertaken in the near future.

APPENDIX.

In the following tables, H denotes the external field, $\frac{\delta l}{l}$ the change of length per unit of length by magnetization, l being the distance between two copper rods screwed to our ferromagnetics, t the temperature, and T the suspended weight.

NICKEL.

$t=-186°$		$t=17.2°$. $T=2kg$.		$t=69°$, $T=2kg$.		$t=143°$, $T=2kg$.	
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	$\frac{\delta l}{l}\times 10^6$
18	− 0.61	12	− 0.93	13	− 0.93	12	− 1.00
37	− 3.90	35	− 5.64	35	− 5.26	35	− 4.79
62	− 9.33	59	−11.90	59	−10.36	60	− 9.42
89	−14.00	87	−17.78	86	−15.85	88	−13.75
123	−18.20	154	−26.38	151	−23.58	152	−19.55
212	−24.32	207	−30.08	205	−26.65	204	−21.58
290	−26.76	282	−32.60	279	−29.20	279	−23.02
395	−29.68	384	−34.62	378	−31.00	382	−24.04
557	−32.88	535	−35.61	541	−31.30	542	−25.50
733	−35.77	706	−36.42	712	−32.08	715	−26.03
910	−37.38	868	−37.00	878	−32.20	870	−26.52

$t=197°$, $T=2kg$.		$t=261°$, $T=2kg$.		$t=346°$, $T=2kg$.		$t=376°$, $T=2kg$.	
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	$\frac{\delta l}{l}\times 10^6$
16	− 1.39	15	− 1.39	12	− 0.62	12	− 0.08
36	− 4.79	35	− 4.72	23	− 1.31	—	—
59	− 8.81	59	− 7.58	35	− 2.01	35	− 0.15
85	−12.45	87	− 9.89	59	− 2.55	59	− 0.23
120	−15.38	153	−11.82	85	− 2.76	87	− 0.46
204	−18.40	200	−12.60	152	− 3.17	152	− 0.54
278	−19 40	277	−13.21	282	− 3.63	282	− 0·58
382	−20.02	381	−13.21	382	− 3.63	382	− 0.54
534	−20.40	531	−13.29	538	− 3.63	542	− 0.54
706	−20.93	702	−13.52	706	− 3.71	715	− 0.54
870	−21.02	868	−13.60	868	− 3.71	875	− 0.54

SOFT IRON.

$t=-186°$		$t=8.4°$, $T=1kg$.		$t=168°$, $T=1kg$.		$t=319°$, $T=1kg$.	
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	$\frac{\delta l}{l}\times 10^6$
37	1.36	24	0.39	24	0.16	23	0.39
60	2.27	60	2.09	63	1.55	62	2.79
89	3.25	90	3.10	94	3.10	92	4.34
124	3.18	110	3.18	115	3.33	112	4.65
—	—	139	3.10	146	3.33	143	4.73
210	1.89	215	2.17	224	2.87	218	465.
286	0.00	292	0.69	300	1.71	294	4.03
393	− 2.34	387	− 0.93	404	0.39	406	3.64
559	− 5.45	570	− 3.53	584	− 1.55	569	2.87
738	− 7.63	757	− 5.42	769	− 2.25	757	2.33
894	− 9.08	932	− 6.28	947	− 3.10	925	2.17

$t=559°$, $T=1kg$.		$t=746°$, $T=0.4kg$.		$t=818°$, $T=0.4kg$.		$t=882°$, $T=0.4kg$	
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	$\frac{\delta l}{l}\times 10^6$
24	0.46	23	0.47	36	0.00	—	—
62	3.26	61	1.86	—	—	—	—
113	5.43	111	2.32	99	0.08	—	—
184	5.81	182	3.10	—	—	—	—
292	6.20	289	3.88	253	0.70	268	0.12
389	6.20	392	4.18	365	1.01	—	—
564	6.20	558	4.26	561	1.55	493	0.23
743	5.81	732	4.65	737	1.78	725	0.70
913	5.66	896	4.65	898	2.17	881	0.97

TUNGSTEN STEEL.

Square prism.				Circular cylinder.			
$t=-186°$		$t=10.0°$		$t=11.5°, T=2kg.$		$t=225°, T=2kg.$	
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	$\frac{\delta l}{l}\times 10^6$
—	—	36	0.23	36	0.23	36	0.46
60	0.76	61	0.92	60	1.52	60	1.90
108	2.59	109	3.20	108	3.61	108	3.66
176	3.89	168	4.58	179	4.41	179	4.11
277	4.65	276	4.73	277	4.72	277	4.57
370	4.42	371	4.58	369	4.72	366	4.57
562	3.89	571	3.97	571	4.34	562	4.34
748	3.66	753	3.28	747	4.03	744	4.00
921	3.20	923	2.98	925	3.73	911	3.88

$t=410°, T=2kg.$		$t=592°, T=1kg.$		$t=722°, T=1kg.$		$t=828°, T=1kg.$	
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	$\frac{\delta l}{l}\times 10^6$
36	0.53	36	1.22	37	0.30	—	—
60	2.13	61	2.13	60	0.76	—	—
108	2.89	108	2.97	107	1.22	—	—
177	3.80	174	3.58	171	1.45	—	—
276	4.03	273	4.34	277	2.06	271	0.08
363	4.34	362	4.50	360	2.44	—	—
558	4.46	554	4.95	549	2.59	552	0.23
732	5.10	720	5.18	708	3.04	723	0.46
888	5.40	891	5.33	867	3.20	881	0·76

CAST COBALT.

$t=17.3°, T=2kg.$		$t=80°, T=2kg.$		$t=155°, T=2kg.$		$t=281°, T=2kg.$	
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	$\frac{\delta l}{l}\times 10^6$
23	− 0.55	22	− 0.47	22	− 0.47	23	− 0.55
35	− 1.49	36	− 1.45	36	− 1.37	35	− 1.33
60	− 3.92	60	− 3.76	60	− 3.33	60	− 2.98
88	− 6.35	88	− 5.72	88	− 5.25	89	− 3.92
122	− 7.68	122	− 6.58	123	− 5.40	123	− 3.14
154	− 7.76	153	− 6.40	154	− 4.86	155	− 1.80
210	− 6.47	206	− 5.53	208	− 2.94	208	+ 0.62
284	− 4.31	282	− 2.43	283	+ 0.16	282	+ 4.62
388	− 1.02	388	+ 1.25	388	+ 4.55	385	+ 8.62
542	+ 3.68	542	+ 6.35	539	+ 9.16	545	+13.87
708	+ 7.76	720	+10.50	710	+13.20	715	+17.40
866	+10.80	874	+13.32	883	+15.82	882	+19.73

$t=515°, T=2kg.$		$t=746°, T=0.4kg.$		$t=911°, T=0.4kg.$		$t=1020°, T=0.4kg.$	
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	$\frac{\delta l}{l}\times 10^6$
24	− 0.27	24	+ 0.19	—	—	—	—
35	− 0.55	48	+ 0.78	48	+ 2.28	—	—
59	− 0.94	—	—	—	—	—	—
87	− 0.08	—	—	—	—	—	—
121	+ 2.35	110	+ 4.12	108	+ 4.73	—	—
206	+ 7.44	182	+ 8.54	247	+ 7.10	—	—
280	+10.97	289	+12.03	—	—	—	—
376	+12.46	395	+14.38	448	+ 9.07	370	+ 2.76
534	+18.02	559	+16.30	663	+10.10	677	+ 3.71
689	+20.61	732	+17.86	—	—	—	—
845	+22.36	903	+18.63	879	+10.64	903	+ 3.94

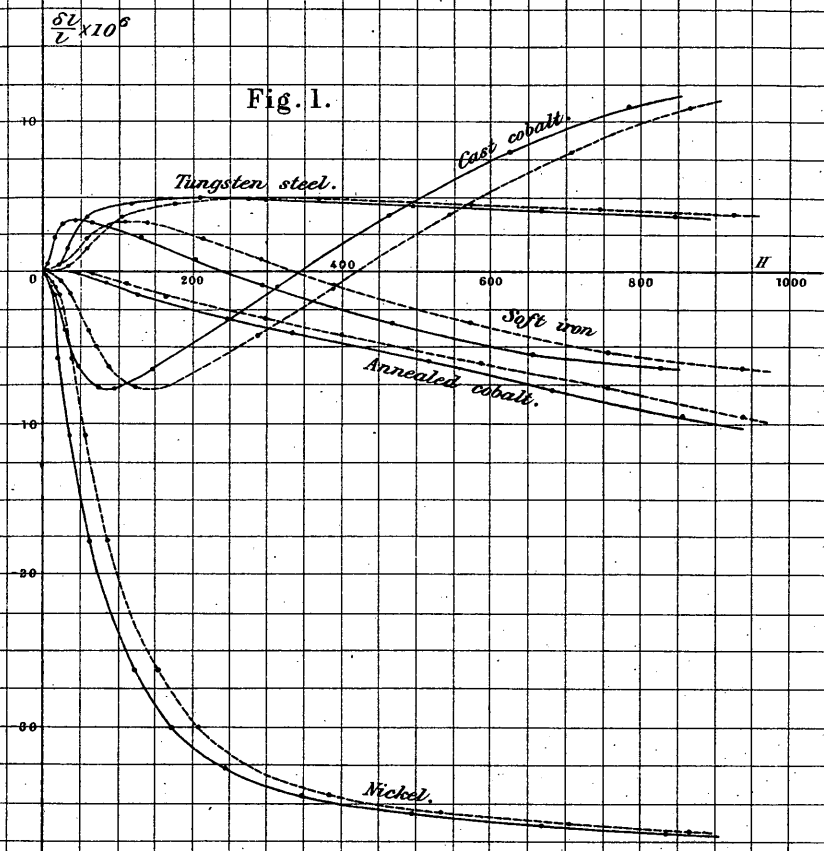
ANNEALED COBALT.

$t=-186°$		$t=9.0°$, $T=2kg.$		$t=166°$, $T=2kg.$		$t=234°$, $T=1kg,$	
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	$\frac{\delta l}{l}\times 10^6$
—	—	—	—	—	—	36	-0.54
60	-0.08	65	-0.19	60	-0.31	62	-1.02
108	-0.16	110	-0.78	115	-1.41	112	-2.97
174	-0.71	161	-1.56	161	-2.54	183	-6.10
275	-1.57	298	-2.97	295	-4.69	292	-9.61
370	-2.52	398	-4.06	399	-6.88	398	-12.98
562	-4.09	586	-5.86	581	-9.30	561	-16.80
739	-6.29	757	-7.81	762	-11.95	749	-19.52
906	-7.86	937	-9.45	932	-14.14	911	-21.64

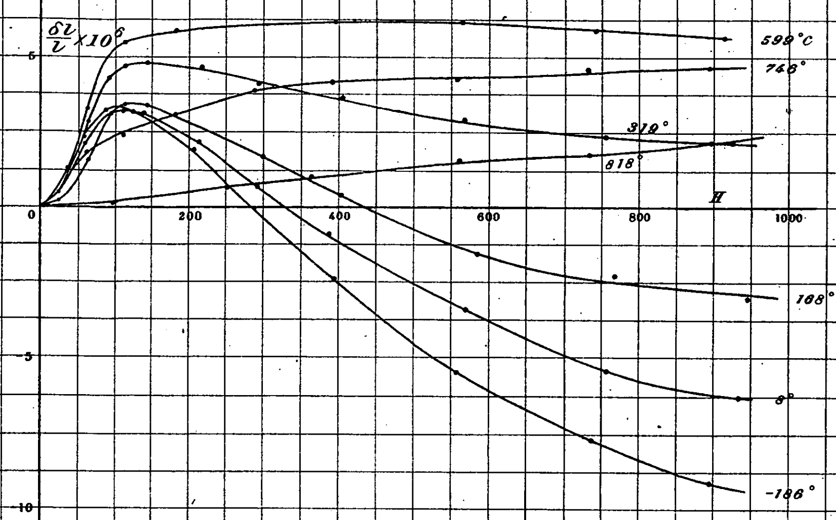
$t=291°$, $T=2kg.$		$t=413°$, $T=2kg.$		$t=451°$, $T=2kg.$		$t=505°$, $T=2kg.$	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
34	-0.98	39	$+0.15$	37	$+0.19$	37	-0.23
62	-3.28	62	$+0.08$	62	$+0.31$	62	-0.70
115	-6.25	110	0.00	112	$+0.63$	112	-0.62
181	-10.16	181	-1.49	181	$+0.63$	182	$+0.55$
295	-13.75	289	-3.52	291	-0.08	290	$+2.97$
398	-15.62	395	-5.47	397	-1.02	395	$+4.69$
575	-17.20	562	-8.52	566	-2.35	564	$+6.18$
749	-17.90	737	-10.00	740	-3.83	732	$+7.19$
920	-18.60	911	-11.56	911	-4.69	910	$+7.97$

$t=592°, T=1kg.$		$t=767°, T=1kg.$		$t=943°, T=1kg.$		$t=1034°, T=0{,}4kg$	
H	$\frac{\delta l}{l} \times 10$	H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{l} \times 10^6$	H	$\frac{\delta l}{} \times 10^6$
36	− 0.19	36	0.00	36	+ 0.23	—	—
60	− 0.47	60	+ 0.19	89	+ 1.95	—	—
111	− 0.16	110	+ 1.95	—	—	124	+ 0.54
181	+ 2.11	179	+ 4.07	175	+ 3.90	—	—
290	+ 5.63	287	+ 7.20	333	+ 5.47	271	+ 1.72
392	+ 7.81	389	+ 9.00	—	—	—	—
560	+10.39	562	+11.10	610	+ 7.27	493	+ 2.34
738	+12.42	732	+12.50	+	—	717	+ 2.74
903	+13.13	898	+13.20	906	+ 7.97	878	+ 3.36

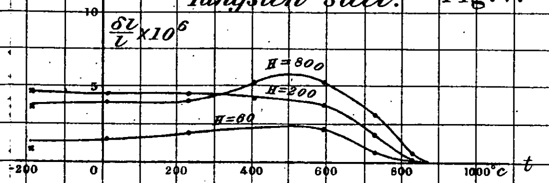
Fig. 1.



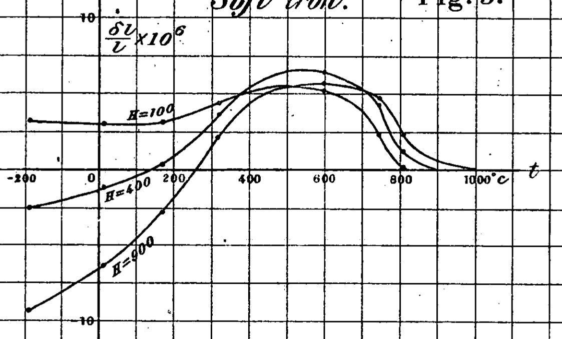
Soft iron. **Fig. 4.**



Tungsten steel. **Fig. 7.**



Soft iron. **Fig. 5.**



Tungsten steel. **Fig. 6.**

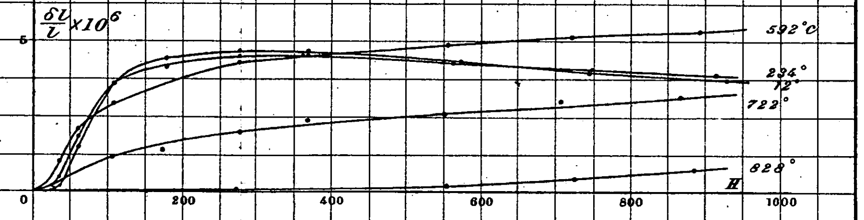


Fig. 2.

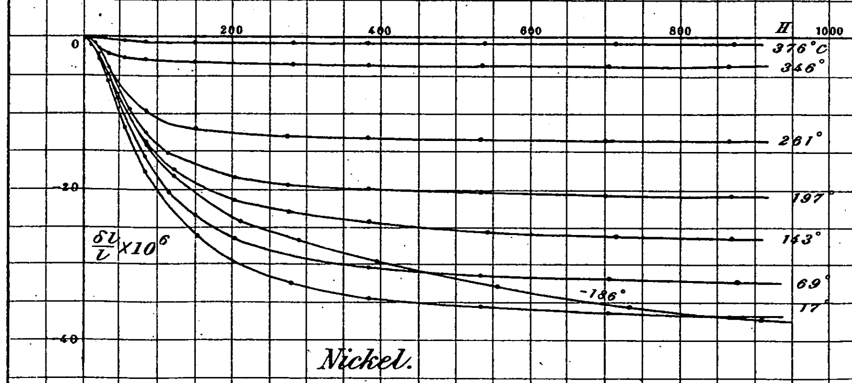
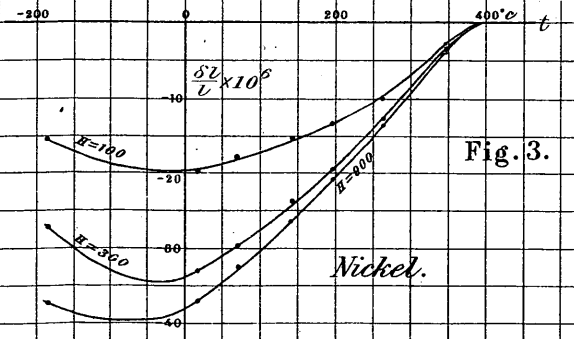
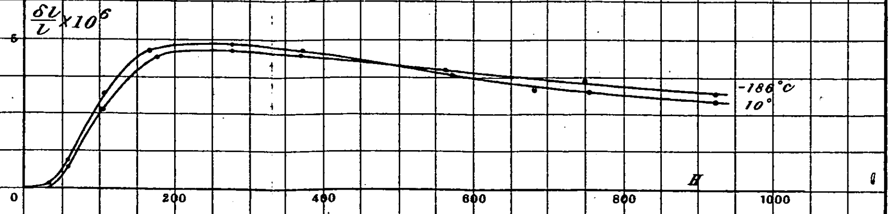


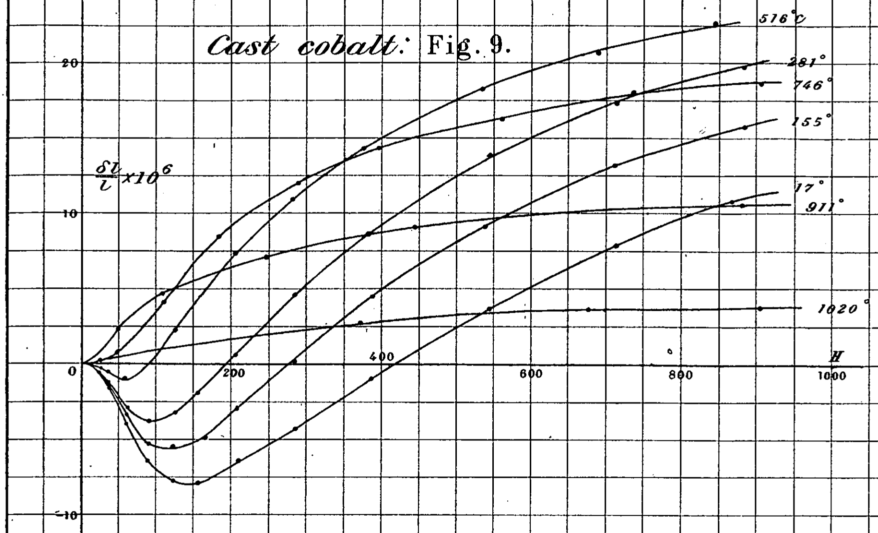
Fig. 3.



Tungsten steel. **Fig. 8.**



Cast cobalt: Fig. 9.



Annealed cobalt. Fig. 11.

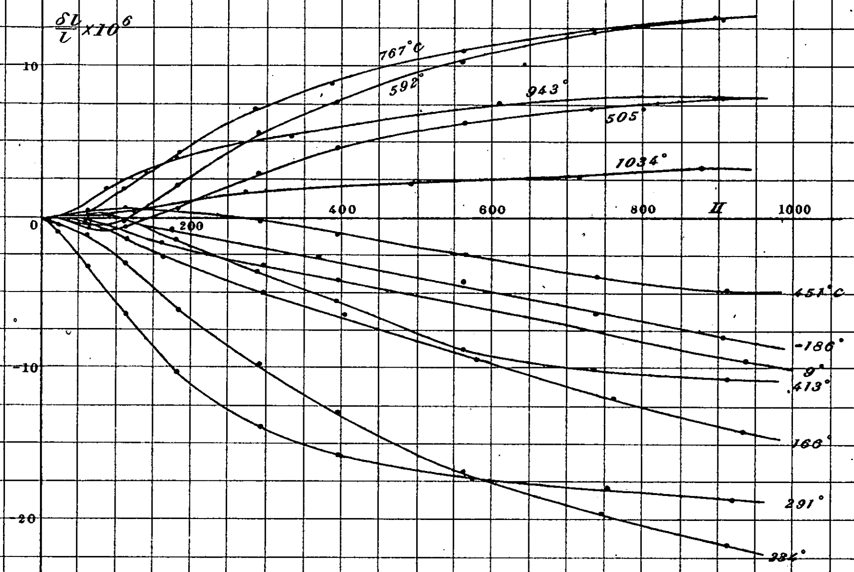
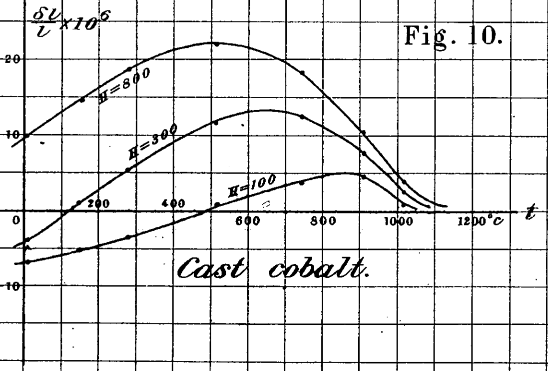


Fig. 10.



Cast cobalt.

Annealed cobalt.

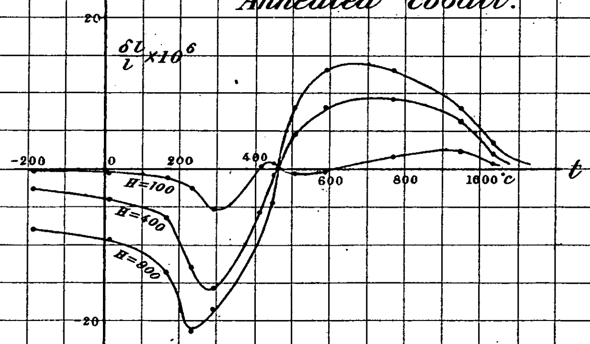


Fig. 12.

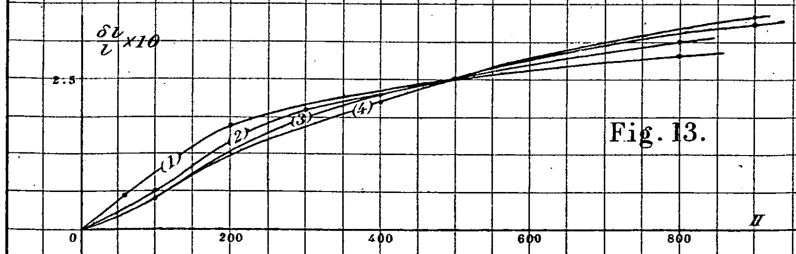
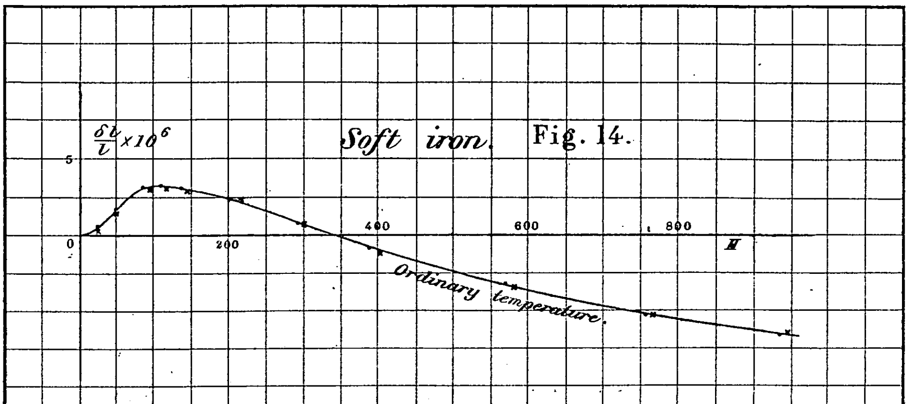
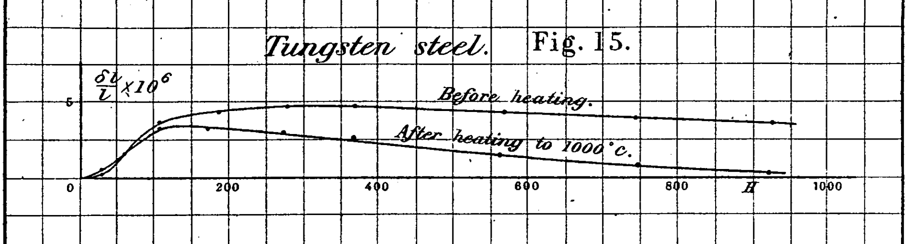


Fig. 13.

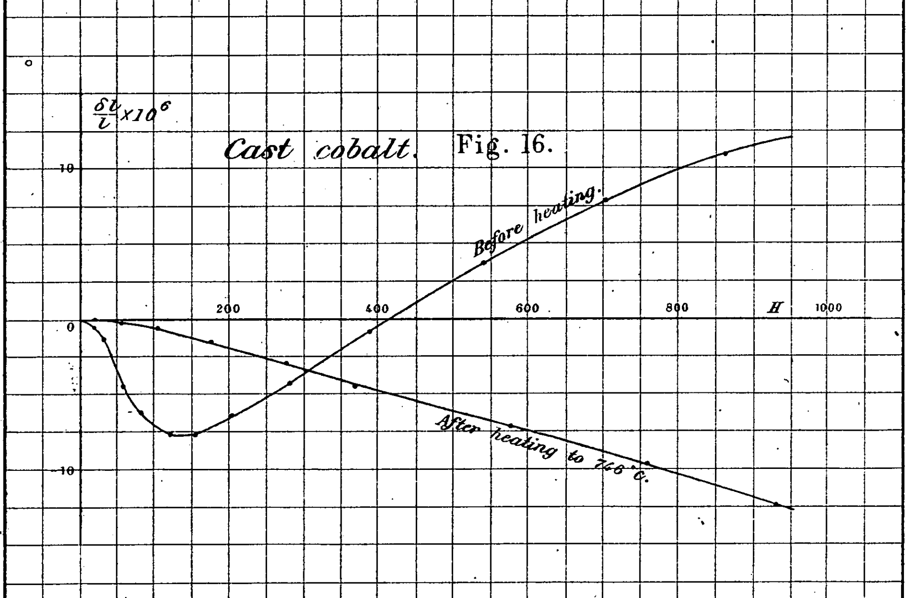
(1) : *Tungsten steel,* 728°C; (3) : *Soft iron,* 788°C.
(2) : *Cast cobalt,* 1034°C; (4) : *Ann. cobalt,* 1032°C.



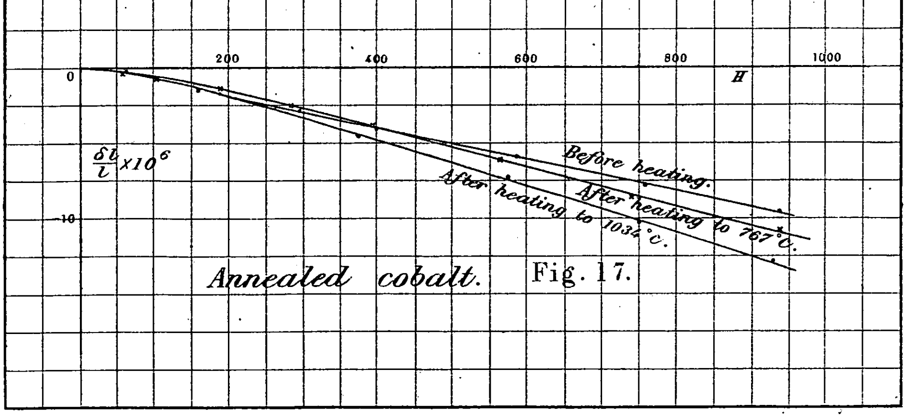
Soft iron. Fig. 14.



Tungsten steel. Fig. 15.



Cast cobalt. Fig. 16.



Annealed cobalt. Fig. 17.