TEMPERATURE COEFFICIENT OF MAGNETIC PERMEABILITY WITHIN THE WORKING RANGE

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1. STATEMENT OF PROBLEM

The development of methods and apparatus for magnetic measurements capable of an accuracy of 1 per cent makes it necessary to consider factors which have heretofore been considered negligible. One of these factors, the temperature coefficient of magnetic permeability, is the subject of the present paper.

Many workers have studied the effects of temperature on the magnetic permeability of iron and steel. All of the investigations, however, have been carried on with special reference to temperatures far removed from the atmospheric range. However, Bauer,[1] Hopkinson,[2] Terry,[3] Burrows,[4] and a few others have made some observations at temperatures between 0 and 100° C. which show that induction curves at two different temperatures in this region cross each other. For low inductions the magnetizing force necessary to produce a certain induction decreases with increase in temperature while for high inductions it increases.

The materials examined by these investigators include soft iron, mild steel, hard steel, electrolytic iron, and nickel. Ewing[5]

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[1] Wied. Ann., **11**, p. 394; 1880.

[2] Phil. Trans., **180**, A, p. 443; 1889.

[3] Phys. Rev., **30**, p. 133; 1910.

[4] This Bulletin, **4**, p. 270; Scientific Paper No. 78.

[5] Magnetic Induction in Iron and Other Metals, p. 178, 3d edition.

states that "the effects which atmospheric fluctuations of temperature exert upon the magnetic quality are too slight to require to be taken account of in specifying the magnetic properties of a sample, or in stating the results of experiments." He gives curves for annealed iron wire and also for the same wire hardened by stretching beyond the elastic limit. The temperatures were 7 or 8° and 100°. The data show that for a given induction changes as high as 0.14 per cent per degree in permeability may occur.

In magnetic measurements at the Bureau of Standards it has been found that for magnetizing forces between 100 and 300 gausses the heating due to the current in the magnetizing coils is sufficient to change quite appreciably the induction corresponding to a given magnetizing force. For this reason it has been the practice, when making measurements where an accuracy of 1 per cent is desired, to immerse the magnetizing coils in oil, which is maintained at a standard temperature of 25°. The present work was undertaken to determine what the magnitude of this temperature effect is and whether it is feasible to apply a correction for the reduction to a standard temperature of data taken at other temperatures.

2. MATERIALS AND APPARATUS

The materials and heat treatments indicated in Tables 1 and 2 were chosen for preliminary work as being representative of the range ordinarily met with in magnetic measurements. The results on this relatively small number of samples are such, however, that further experimental work appears to be unnecessary.

TABLE 1.—Chemical Composition

	Carbon	Sulphur	Phosphorus	Manganese	Silicon
Cast-iron	3.65	0.074	0.656	0.52	1.57
Wrought-iron	.053	.028	.155	.15	.15
Low-carbon steel	.073	.036	.100	.33	.10

TABLE 2.—Heat treatment

Designation	Material	Heat treatment
C-1	Cast iron	As received.
C-2	do	Quenched from 1000°.
C-3	do	Annealed from 900°.
W-1	Wrought iron	As received.
W-2	do	Annealed from 900°.
S-1	Low-carbon steel	As received.
S-2	do	Annealed from 900°.

The magnetic measurements were made by the usual ring method. This method presents the fewest experimental difficulties and yields reliable results. In the ring method two assumptions are made: First, that the average value of the magnetizing force is that at the center of the cross section; and, second, that the permeability is constant within the limits of the magnetizing force across the section. The dimensions of the rings are such that the errors due to these assumptions are negligible, but even though they were much greater they enter to the same extent at all temperatures, and therefore would not introduce any error in the temperature coefficients which are obtained by difference. The error due to magnetic viscosity was rendered negligible by making the rings of small cross section and using a long-period galvanometer (30 seconds). The constants of the rings and windings are shown in Table 3.

TABLE 3.—Constants of Rings and Windings

Ring	Density	Mass	Mean diameter	Radial width	Cross section	Mean length	Magnetizing turns	$\frac{H}{I}$	Turns in test coil	Thermometer resistance at 25°
C-1	7.06	615	11.4	1.0	2.43	35.8	312	10.95	100	1.9334
C-2	6.96	653	11.4	1.0	2.62	35.8	305	10.71	100	1.7729
C-3	6.86	648	11.4	1.0	2.64	35.8	295	10.36	100	1.7933
W-1	7.67	380	10.8	.6	1.46	33.9	317	11.75	100	1.6296
W-2	7.55	399	10.8	.6	1.56	33.9	305	11.31	100	2.0231
S-1	7.83	283	8.4	.5	1.38	26.2	222	10.65	100	1.6104
S-2	7.76	285	8.4	.5	1.40	26.2	231	11.08	100	1.7727

The temperature measurements were made by means of a resistance thermometer, consisting of two turns of silk-covered copper wire wound around the outer circumference of the ring. The measuring current of 0.1 ampere produces, therefore, no component of magnetizing force in the direction of the magnetic flux within the iron. The wire was separated from the iron by only a single layer of thin paper, so that its temperature may be assumed as equal to that of the iron itself. Separate potential leads were brought out and the resistance of the part of the wire next to the iron determined by measuring the potential drop across it when 0.1 ampere was flowing. The current and voltage measurements were made with a potentiometer and a standard resistance. The thermometers were calibrated by measuring their resistances when placed in an oil bath at known temperatures. No error is introduced by the heating of the current in the thermometer coils, since the calibrations are made under working conditions. The resistance of the thermometer wires was of the order of 1.5 ohms with a change per degree of about 0.006 ohm, so that measurements could easily be made to 0.1° C, which was ample for the purpose.

The induction was measured in terms of the deflections of a ballistic galvanometer calibrated by means of a mutual inductance. The test coil of 100 turns was wound as closely to the iron as the thermometer wire would permit so as to inclose only the flux in the iron itself.

The magnetizing winding consists of two layers of No. 14 double-cotton covered wire, separated from the other windings by cotton tape. The concentration of the winding is such that the magnetizing force is about ten times the current. The magnetizing current was found by measuring the potential drop across a standard resistance by means of a potentiometer. The magnetizing coils of all of the rings were connected in series. This arrangement allows all of the rings to be demagnetized at one operation and also requires but one adjustment of current for each value of the magnetizing force used.

An oil bath was employed for regulating temperature during the magnetic measurements. The tank was provided with an outer compartment which could be packed with ice for the low temperature. The higher temperatures were secured by means of an electric heating coil placed directly in the oil. The use of oil, which was kept in circulation by a motor-driven stirrer, served to maintain the rings at a unifrom temperature.

3. OBSERVATIONS AND RESULTS

The magnetic measurements were made at different temperatures in the following order: 25°, 88°, 25°, 3°, 25°. The 25° readings were repeated to determine whether any permanent change had taken place in the material. The first set of observations did show a change in some of the rings, and it was found necessary to alternately heat and cool them a number of times in order to bring the material to a stable state. This progressive decrease in permeability due to heating has been observed before [6] and is termed "aging."

Table 4 gives an example of this aging effect, which was most marked in the wrought iron as received and steel as received.

TABLE 4.—Aging Effect in Steel as Received

Induction (gausses)	Magnetizing force (gausses) at 25° C		Induction (gausses)	Magnetizing force (gausses) at 25° C	
	Before heating	After heating to 88°		Before heating	After heating to 88°
2000	2.02	2.31	10 000	7.86	9.02
4000	2.83	3.28	12 000	12.1	13.9
6000	3.89	4.47	14 000	21.1	24.3
8000	5.42	6.28	16 000	47.2	53.0

This shows an average change of about 15 per cent in magnetizing force for a given induction due to aging. The values for wrought iron show the same order of magnitude. It is obvious that temperature coefficients can not be determined until the material has been brought to a stable state. When the stable condition had been reached the oil bath was adjusted successively to temperatures of approximately 3°, 25°, and 88°, and normal induction measurements made. No attempt was made to keep the temperature strictly constant, but small variations from the

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[6] Mazotto, N. Cimento, 7, pp. 393–421, June, and 8, pp. 5–27, July, 1904; abstracted in Sc. Ab. B 955; 1904.

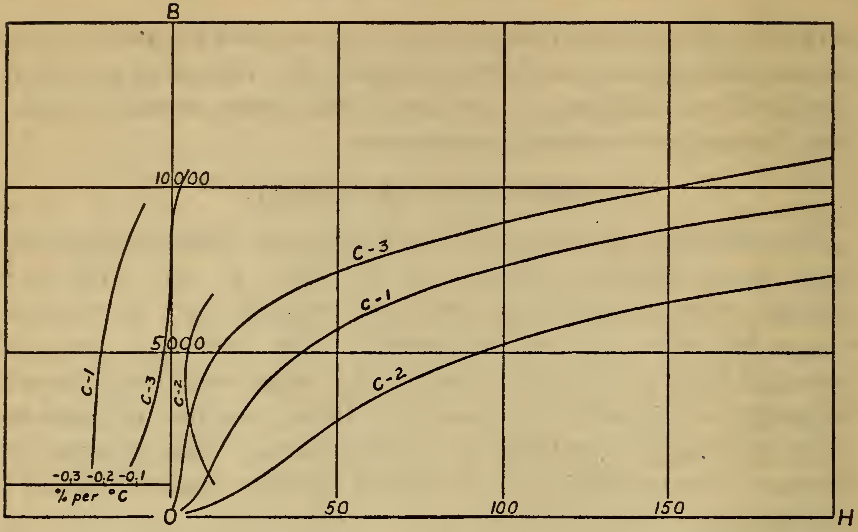

FIG. 1.—*Showing normal induction for cast iron at 25° and percentage change in magnetizing force for a given induction due to 1 degree rise in temperature*

C–1, as received C–2, quenched from 1000° C–3, annealed from 900°

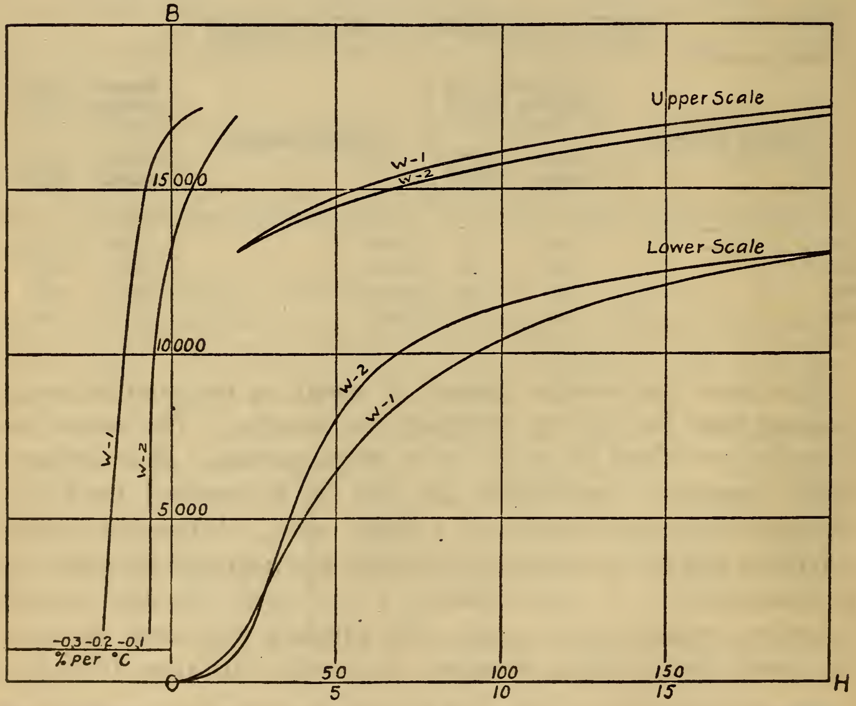

FIG. 2.—*Showing normal induction for wrought iron at 25° and percentage change in magnetizing force for a given induction due to 1 degree rise in temperature*

W–1, as received W–2, annealed from 900°

standard temperature were permitted. As the temperature was actually determined for each point the coefficient of induction for a given magnetizing force could be calculated from the data at two temperatures. In order to draw curves for the standard temperatures 3°, 25°, and 88°, corrections were applied to the observed values by means of these temperature coefficients. From these curves the coefficients of magnetizing force corresponding to a given induction were determined. The values calculated from these three curves indicate that, within the limits of experimental error, the temperature coefficient in this range is independent of temperature.

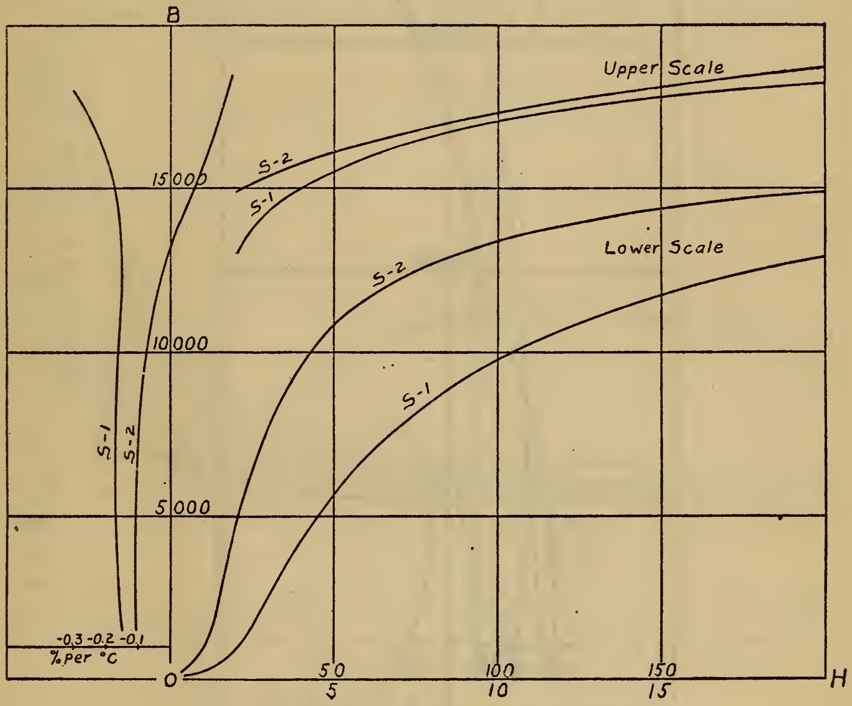

Fig. 3.—*Showing normal induction for low-carbon steel at 25° and percentage change in magnetizing force for a given induction due to 1 degree rise in temperature*

S–1, as received S–2, annealed from 900°

Figs. 1, 2, and 3 give the normal induction curves at 25° and the temperature coefficients in terms of the percentage change per degree in the magnetizing force corresponding to a given induction. It will be noted that the temperature coefficient

FIG. 4.—*Showing percentage change in magnetizing force for a given induction due to 1 degree rise in temperature*

C–1, cast iron as received
C–2, cast iron quenched from 1000°
C–3, cast iron annealed from 900°
W–1, wrought iron as received
W–2, wrought iron annealed from 900°
S–1, low-carbon steel as received
S–2, low-carbon steel annealed from 900°

changes sign in some cases and not in others. The wrought iron both as received and annealed shows this change, while the steel shows it only in the annealed condition. Cast iron shows quite different characteristics, according to the heat treatment it has received. In the material as received the values of the coefficient are all negative, though they decrease in magnitude with increase in induction. For the annealed material the temperature coefficient is negative at low inductions and positive at high inductions, while for the quenched specimen the values are all positive.

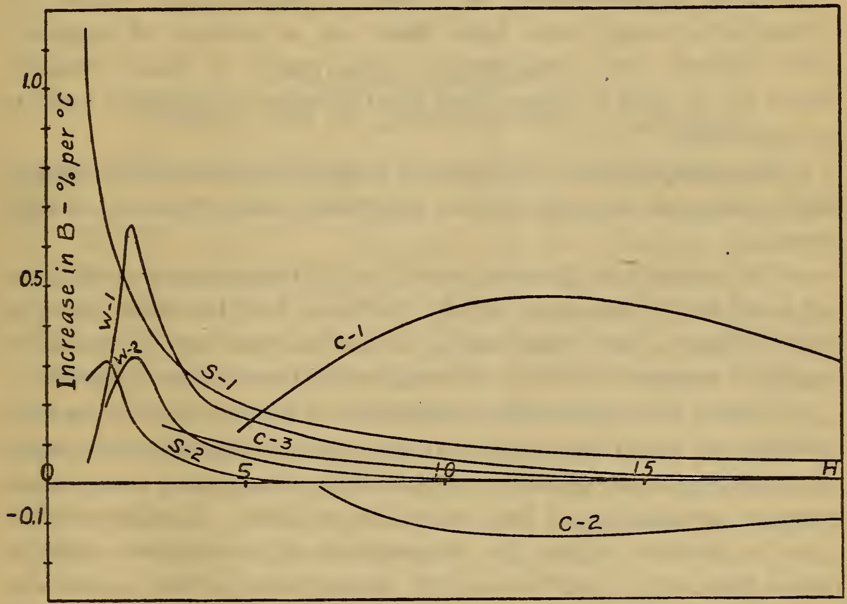

Fig. 5.—*Showing percentage change in induction for a given magnetizing force due to 1 degree rise in temperature*

C–1, cast iron as received
C–2, cast iron quenched from 1000°
C–3, cast iron annealed from 900°
W–1, wrought iron as received
W–2, wrought iron annealed from 900°
S–1, low-carbon steel as received
S–2, low-carbon steel annealed from 900°

Figs. 4 and 5 bring together the coefficients for all of the materials. Fig. 4 shows the percentage change per degree in magnetizing force for a given induction, while Fig. 5 shows the percentage change per degree in induction for a given magnetizing force. The maximum percentage change in induction occurs at comparatively low magnetizing forces, while the percentage change in magnetizing force shows no such well-defined maximum. From these figures it can also be seen how great a variation there is, not only with different kinds of material, but in the same material which has received different heat treatments.

SUMMARY

Magnetic measurements at different temperatures within the atmospheric range have been made on a number of materials with different heat treatments. The results of these measurements are of such a nature that the following conclusions seem to be warranted:

1. The temperature coefficient of magnetic permeability, though small, can not be neglected in magnetic measurements of high accuracy.

2. On account of the wide variation in temperature coefficient, not only for different materials, but also for the same material with different heat treatments, correction can not be made to standard temperature from data obtained from other materials.

3. Unless the temperature coefficient is known for the particular material under test, temperature control offers the only means of avoiding the error due to temperature changes, at least where errors as great as 1 per cent are to be avoided. Conditions often arise in practice where the temperature of a specimen may be raised from 10° to 20° above the temperature of the room, due either to a comparatively heavy current or to the use of coils already heated from a previous test. Since temperature coefficients may be as great as 0.3 per cent per degree, errors amounting to 2 per cent or more may exist.

These conclusions hold in general, even though there may be materials which have very small or even zero temperature coefficients.

The author is indebted to Dr. C. W. Burrows for many valuable suggestions throughout the course of the work, also to the chemistry division of the Bureau for chemical analyses and the division of metallurgy for the heat treatment of the specimens.

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