IEC 60404-15

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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Magnetic materials –
Part 15: Methods for the determination of the relative magnetic permeability of feebly magnetic materials

Matériaux magnétiques –
Partie 15: Méthodes de détermination de la perméabilité magnétique relative des matériaux faiblement magnétiques

IEC 60404-15:2012

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MAGNETIC MATERIALS –

Part 15: Methods for the determination of the relative magnetic permeability of feebly magnetic materials

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International Standard IEC 60404-15 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

The text of this standard is based on the following documents:

FDIS	Report on voting
68/442/FDIS	68/443/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 60404 series, under the general title *Magnetic materials*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

The determination of the relative magnetic permeability of feebly magnetic materials is often required to assess their effect on the ambient magnetic field. Typical feebly magnetic materials are austenitic stainless steels and "non-magnetic" brass.

The relative magnetic permeability of some of these materials can vary significantly with the applied magnetic field strength. In the majority of cases, these materials find application in the ambient earth's magnetic field. This field in Europe is 35 A/m to 40 A/m, in the far East, it is 25 A/m to 35 A/m and in North America, it is 25 A/m to 35 A/m. However, at present, methods of measurement are not available to determine the relative magnetic permeability of feebly magnetic materials at such a low value of magnetic field strength.

Studies of the properties of feebly magnetic materials have been carried out, primarily with a view to the production of improved reference materials. These studies have shown [1][1] that it is possible to produce reference materials which have a substantially constant relative magnetic permeability over the range from the earth's magnetic field to at least a magnetic field strength of 100 kA/m.

Since conventional metallic materials can also be used as reference materials their relative magnetic permeability can be determined using the reference method. It is important that the magnetic field strength used during the determination of the relative magnetic permeability is stated for all materials but in particular for conventional materials since the changes with applied magnetic field can be large. This behaviour also needs to be considered when using reference materials made from conventional materials to calibrate comparator methods. This is because these methods use magnetic fields that vary through the volume of the material being tested and this makes it difficult to know the relative magnetic permeability to use for the calibration.

Where the effect of a feebly magnetic material on the ambient earth's magnetic field is critical, the direct measurement of this effect using a sensitive magnetometer should be considered.

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1 Figures in square brackets refer to the bibliography.

MAGNETIC MATERIALS –

Part 15: Methods for the determination of the relative magnetic permeability of feebly magnetic materials

1 Scope

This part of IEC 60404 specifies a solenoid method, a magnetic moment method, a magnetic balance method and a permeability meter method for the determination of the relative magnetic permeability of feebly magnetic materials (including austenitic stainless steel). The magnetic balance and permeability meter methods are both comparison methods calibrated using reference materials to determine the value of the relative magnetic permeability of the test specimen. The relative magnetic permeability range for each of these methods is shown in Table 1. The methods given are for applied magnetic field strengths of between 5 kA/m and 100 kA/m.

Table 1 – Relative magnetic permeability ranges for the methods described

Measurement method	Relative magnetic permeability range
Solenoid	1,003 to 2
Magnetic moment	1,003 to 1,2
Magnetic balance	1,003 to 5
Permeability meter	1,003 to 2

NOTE 1 The relative magnetic permeability range given for the magnetic balance method covers the inserts provided with a typical instrument. These can only be assessed at values for which calibrated reference materials exist.

NOTE 2 For a relative magnetic permeability larger than 2, a reference material cannot be calibrated using this written standard. A note of this is given in the test report explaining that the values measured using the magnetic balance are for indication only.

The solenoid method is the reference method. The magnetic moment method described is used mainly for the measurement of the relative magnetic permeability of mass standards.

Two comparator methods used by industry are described. These can be calibrated using reference materials for which the relative magnetic permeability has been determined using the reference method. When suitable, the magnetic moment method can also be used. The dimensions of the reference material need to be given careful consideration when determining the uncertainty in the calibration value due to self-demagnetization effects. See Annex A for more information on correcting for self-demagnetization.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at <http://www.electropedia.org/>)

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-221, IEC 60050-121 as well as the following apply.

3.1
self-demagnetization
generation of a magnetic field within a magnetized body that opposes the magnetization

3.2
demagnetize
to bring a magnetic material to a magnetically neutral state

3.3
feebly magnetic material
material that is essentially non-magnetic in character

4 Solenoid and magnetic moment method

4.1 General

The methods that are described in Clause 4 are reference methods for determining the relative magnetic permeability of test specimens of feebly magnetic materials with a length to diameter ratio of at least 10:1. When the relative magnetic permeability is less than 1,2, it is possible to use a moment detection coil and a test specimen with a length to diameter ratio of 1:1. Both methods use similar equipment and involve similar calculations to determine the relative magnetic permeability. The descriptions of both methods are therefore presented together here with significant differences explained in the text.

4.2 Principle

The relative magnetic permeability of a feebly magnetic test specimen is determined from the magnetic polarization J and the corresponding magnetic field strength H measured using the circuit shown in Figure 1, using

$$\mu_r = 1 + \frac{J}{\mu_0 H} \tag{1}$$

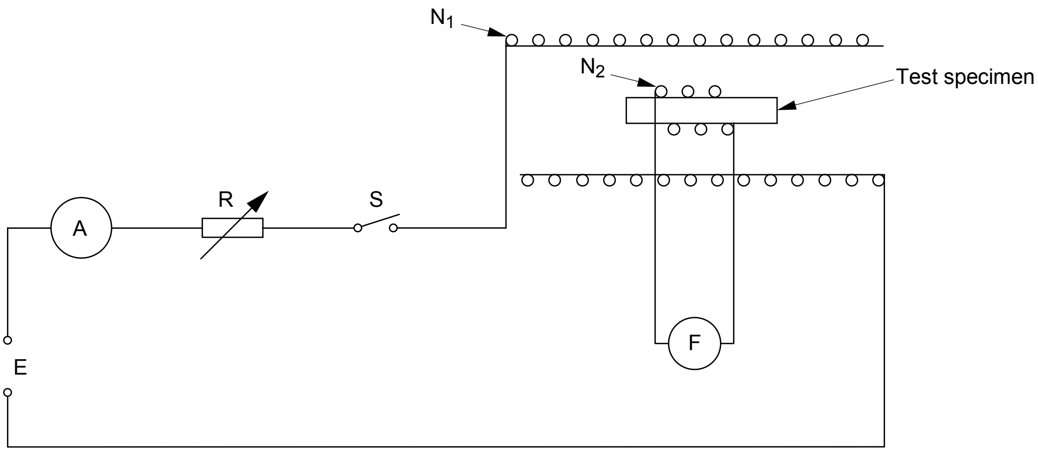
where

μ_r is the relative magnetic permeability of the test specimen (ratio);

μ_0 is the magnetic constant ($4\pi \times 10^{-7}$) (in H/m);

J is the magnetic polarization (in T);

H is the magnetic field strength (as calculated from the magnetizing current and the magnetic field strength to current ratio (known as the coil constant) for the solenoid) (in A/m).



Key

A current measuring device or ammeter

E d.c. supply

F flux integrator

N_1 solenoid

N_2 search coil or magnetic moment detection coil

R variable resistor (controlling magnetizing current)

S switch

Figure 1 – Circuit diagram for the solenoid method

NOTE In Figure 1, the search coil N_2 is replaced by a moment detection coil for the magnetic moment method.

4.3 Apparatus

4.3.1 *Solenoid.* The solenoid shall have a length to diameter ratio of not less than 10:1 or, in the case of lower length, it shall contain coaxial supplementary coils at the ends or it shall consist of a split pair coil system (Garrett [2]). The last two coil systems shall yield at least the same degree of field homogeneity in the centre as is obtained with the long solenoid. The coils shall be wound on non-magnetic, non-conducting formers. The winding shall have a sufficient number of turns of wire to be capable of carrying a current that will produce a magnetic field strength of 100 kA/m. The magnetic field to current ratio of the solenoid (known as the coil constant) shall be determined with an uncertainty of ± 0,5 % or better, either by an independent calibration or alternatively by measuring the magnetic field strength by means of a calibrated Hall effect probe and by measuring the corresponding magnetizing current (using the method described in 4.3.5).

NOTE 1 More than one solenoid (or split pair coil system) may be required to cover the complete range of magnetic field strength.

NOTE 2 The optimal diameter of the solenoid depends upon the diameter of test specimens to be measured and the sensitivity of the measurement. For measurements on bars up to 30 mm in diameter having a relative magnetic permeability of 1,005, the internal diameter of the solenoid would be approximately 80 mm to accommodate the requisite search coil.

4.3.2 *Search coil*. The search coil shall be wound on a non-magnetic, non-conducting former. Typically, for test specimens up to 30 mm in diameter, the internal diameter of the aperture in the search coil is 32 mm to allow test specimens to be freely inserted and withdrawn. The length of the winding shall be 40 mm; end cheeks of between 75 mm and 80 mm diameter shall be fitted to the former. The winding can be, for example, 10 000 turns of 0,2 mm diameter insulated wire with interleaving as necessary.

NOTE The winding may be tapped at intervals to facilitate the adjustment of the sensitivity of the measuring system when determining the relative magnetic permeability of test specimens in the higher part of the permeability range.

4.3.3 For much shorter solid right cylinders with a length to diameter ratio of 1:1, a moment detection coil with a homogeneous sensitivity over the volume of the test specimen shall be used for measuring the magnetic dipole moment of the cylinder (see Figure 2). The magnetic polarization is calculated from

$$J = \frac{j}{V} \tag{2}$$

where

j is the magnetic dipole moment (in Wbm);

V is the volume of the test specimen (in m^3).

The moment detection coil can be a solenoid with additional homogenizing windings close to the ends of the coil.

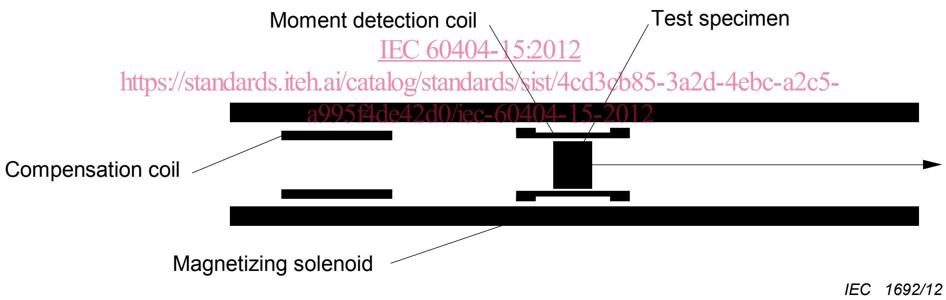


Figure 2 – Coil system for the determination of the magnetic dipole moment

The measurement of the magnetic moment of short cylinders with a length to diameter ratio of 1:1 shall be restricted to materials having a relative permeability smaller than μ_r = 1,2. If this condition is not met, the magnetic field strength inside the test specimen and the polarization become inhomogeneous and this will produce significant errors in the measured relative magnetic permeability.

In the region μ_r = 1,003 to 1,2, a linear correction for the effect of the self-demagnetizing field is appropriate. See Annex A for more information.

NOTE Typically, weight pieces of the classes E_1, E_2 and F_1 according to OIML R111-1 (2004) [3] fall into this range.

For this correction, equation (A.2) of Annex A is to be used together with the value of the magnetometric self-demagnetization factor N_m as obtained from reference [6].

For example, for a cylindrical sample with a 1:1 aspect ratio, values of the relative correction to the applied magnetic field for different relative magnetic permeabilities due to self-demagnetization are given in Table 2.

Table 2 – Cylindrical sample with a 1:1 aspect ratio

μ_r	N_m	$\Delta H/H$
1,000 1	0,311 6	0,003 %
1,007	0,311 4	0,22 %
1,2	0,309 3	6,2 %

$\Delta H/H$ is the relative correction of the magnetic field strength and N_m is the magnetometric self-demagnetization factor.

This is discussed in more detail in Annex A.

4.3.4 *Flux integrator.* The flux integrator shall be an electronic charge integrator or similar device, calibrated with an uncertainty of ± 0,5 % or better.

4.3.5 *Current measuring device.* The current measuring device shall consist of a calibrated resistor connected in series with the magnetizing circuit and a calibrated digital voltmeter.

The magnetizing current shall be determined from the measurement of the voltage developed across the resistor. The combined uncertainties of the resistor and voltmeter shall be such that the magnetizing current can be determined with an uncertainty of ± 0,2 % or better. Alternatively, an ammeter calibrated with an equivalent uncertainty can be used.

4.3.6 *Micrometer*. The micrometer for measuring the transverse dimensions of the test specimen for the solenoid method shall be calibrated. For the magnetic moment method, the volume is required and appropriate dimensional measurements shall be made.

4.4 Test specimen for the solenoid method

The test specimen shall consist of a round or rectangular bar, or a number of strips or wires having a total cross-sectional area of at least 100 mm^2. The maximum cross-sectional area shall be determined by the diameter of the central aperture of the search coil. Allowance shall be made for the easy insertion and withdrawal of the test specimen without disturbing the position of the search coil.

To avoid significant errors introduced by self-demagnetization, the length to equivalent diameter ratio of the test specimen shall be not less than 10:1. When corrections for self-demagnetization are required see Annex A.

For example, values are given in Table 3 for a rod of circular cross section with an aspect ratio of 10:1, a diameter of 30 mm and a search coil with an effective average diameter of 52,2 mm. The relative corrections to the applied magnetic field strength and the magnetic polarization for different relative magnetic permeabilities due to self-demagnetization are shown.

Table 3 – Circular cross section rod with an aspect ratio of 10:1

μ_r	N_f	$\Delta H/H$	$\Delta J/J$
1,000 1	0,004 927	0,000 %	1,49 %
1,007	0,004 931	0,003 %	1,49 %
1,2	0,005 054	0,101 %	1,53 %
2	0,005 541	0,554 %	1,68 %

$\Delta H/H$ is the relative correction of the magnetic field strength, N_f is the fluxmetric self-demagnetization factor and $\Delta J/J$ is the relative correction of the magnetic polarization.

This is discussed in more detail in Annex A.

4.5 Procedure

4.5.1 The cross-sectional area of the test specimen shall be established from a number of measurements of each dimension. For a test specimen for the solenoid method, the diameter or transverse dimensions shall be measured by means of a calibrated micrometer (see 4.3.6) at approximately 10 mm intervals along the central 40 mm of length. The mean cross-sectional area, expressed in square metres, shall be calculated from the mean dimensions, with an uncertainty of ± 0,5 %. The difference between the greatest and least cross-sectional areas shall not exceed ± 0,5 % of the mean area.

For a test specimen for the magnetic moment method, the determination of the volume is required and sufficient dimensional measurements shall be made so that this can be determined with an uncertainty of ± 0,71 % (this is the square root of the sum of the squares of 0,5 % for the cross section and 0,5 % for the length).

4.5.2 The calibration of the flux integrator shall be established with an uncertainty of ± 0,5 % or better. In order to do this, the secondary winding of a calibrated mutual inductor is connected in series with the search coil and flux integrator and the current flowing in the primary winding of the mutual inductor is changed to give the change in magnetic flux required. From the integrator reading, equation (3) is used to determine the calibration constant of the integrator.

$$k\Phi_{IR} = M\Delta I \quad (3)$$

where

k is the calibration constant of the flux integrator;

Φ_{IR} is the flux integrator reading (in Wb);

M is the mutual inductance for the calibration (in H);

ΔI is the change in primary current in the mutual inductor (in A).

NOTE It is important that the total winding resistance at the input of the integrator is the same for calibration and measurements on the test specimen. To avoid the possibility of coupling of the search coil or moment coil to the mutual inductor, a non-inductive resistance equivalent to the secondary of the mutual inductor can be placed in series with the search coil or the moment coil.

4.5.3 The test specimen shall be demagnetized immediately prior to the measurement from a magnetic field strength of not less than 20 kA/m by the slow reversal of a gradually reducing direct current or a gradually reducing alternating current (for the frequency, see next paragraph), provided the magnetic field produced by the latter can completely penetrate the test specimen. Test specimens which have been subjected to a higher magnetic field strength shall be demagnetized from a suitably high magnetic field before measurement. The effectiveness of the demagnetization shall be checked by inserting the test specimen into the search coil or moment detection coil and, with no current flowing, withdrawing the test specimen and observing the reading on the flux integrator. There shall be either a zero reading or an insignificantly small reading on the flux integrator.

In order that the magnetic field may completely penetrate the test specimen, the frequency of reversal shall not exceed 0,5 Hz for a cross-section of 10 mm × 10 mm and 0,1 Hz for a cross-section of 20 mm × 20 mm. Some materials may also display magnetic viscosity effects so that even slower reversals are required to ensure complete demagnetization. In cases of doubt, the effect of slower and more rapid reversals shall be compared.