



BSI Standards Publication

Electromagnetic compatibility (EMC)

Part 4-23: Testing and measurement techniques — Test methods for protective devices for HEMP and other radiated disturbances

National foreword

This British Standard is the UK implementation of IEC 61000-4-23:2016+A1:2025. It supersedes BS IEC 61000-4-23:2016, which is withdrawn.

The start and finish of text introduced or altered by amendment is indicated in the text by tags. Tags indicating changes to IEC text carry the number of the IEC amendment. For example, text altered by IEC amendment 1 is indicated by A1 A1.

The UK participation in its preparation was entrusted to Technical Committee GEL/210, EMC - Policy committee.

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INTERNATIONAL STANDARD

BASIC EMC PUBLICATION

**Electromagnetic compatibility (EMC) -
Part 4-23: Testing and measurement techniques - Test methods for protective
devices for HEMP and other radiated disturbances**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

Electromagnetic compatibility (EMC) - Part 4-23: Testing and measurement techniques - Test methods for protective devices for HEMP and other radiated disturbances

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International Standard IEC 61000-4-23 has been prepared by subcommittee 77C: High power transient phenomena, of IEC technical committee 77: Electromagnetic compatibility.

It forms Part 4-23 of IEC 61000. It has the status of a basic EMC publication in accordance with IEC Guide 107.

This second edition cancels and replaces the first edition published in 2000. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) updates to the shielding effectiveness (SE) test method in Clause 5;
- b) a new Annex F describing methods for testing 'inside-to-out' has been added.

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

CDV	Report on voting
77C/253/CDV	77C/257/RVC

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 parts in the IEC 61000 series, published under the general title *Electromagnetic compatibility (EMC)*, 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 website 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
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INTRODUCTION

IEC 61000 is published in separate parts, according to the following structure:

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description of the environment

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

Immunity limits (in so far as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques

Measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic Standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as international standards, as technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: IEC 61000-6-1).

The IEC has initiated the preparation of standardized methods to protect civilian society from the effects of high power electromagnetic (HPEM) environments. Such effects could disrupt systems for communications, electric power, information technology, etc.

This part of IEC 61000 is an international standard that establishes the test concepts, set-ups, required equipment, and test procedures for protective devices against HEMP radiated disturbances.

Annex F provides examples of the SE test method placing the TX antenna inside the barrier.

1 Scope

This part of IEC 61000 provides a protective devices test method for HEMP and other radiated disturbances. It is primarily intended for HEMP testing but can be applied to other externally generated radiated disturbances where appropriate. It provides a brief description of the most important concepts for testing of shielding elements. For each test, the following basic information is provided:

- theoretical foundation of the test (the test concepts);
- test set-up including outside-to-in and inside-to-out measurements;
- required equipment;
- test procedures;
- data processing.

This international standard does not provide information on requirements for specific levels for testing.

This part of IEC 61000 has been updated to include a new test method.

Due to the available space, a transmitting antenna position outside the barrier has mainly been suggested. However, nowadays, many EMP protection facilities in practical use do not actually have enough space available outside the electromagnetic barrier due to physical constraints such as concrete walls or soil to allow the method described in IEC 61000-4-23:2000 (edition 1) to be applied correctly. From experience many facilities have available space for a 1 m separation or less only.

Therefore, in many practical cases it is not possible to measure shielding effectiveness according to the test method of previous documents. The constructors for EMP protection facilities are also unwilling to build facilities with extra space for measurements with the transmitting antenna outside the barrier due to the great expense and inefficiency of the operational working area for new or existing buildings.

This document provides additionally a method that allows the transmitting antenna to be placed inside the enclosure and the receiving antenna outside the barrier ('inside-to-out' method). Annex F includes test set-up and procedure examples.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-161, *International Electrotechnical Vocabulary (IEV) – Part 161: Electromagnetic compatibility* (available at www.electropedia.org)

IEC 61000-2-9, *Electromagnetic compatibility (EMC) – Part 2: Environment – Section 9: Description of HEMP environment – Radiated disturbance*

IEC 61000-5-3, *Electromagnetic compatibility (EMC) – Part 5-3: Installation and mitigation guidelines – HEMP protection concepts*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-161, as well as the following apply.

3.1

aperture

opening in an electromagnetic barrier (shield) through which EM fields may penetrate

3.2

aperture point-of-entry

intentional or inadvertent holes, cracks, openings or other discontinuities in a shield surface

Note 1 to entry: Intentional aperture points-of-entry are provided for personnel and/or equipment entry and egress and for ventilation through an electromagnetic barrier.

3.3

attenuation

reduction in magnitude (as a result of absorption and scattering) of an electric or magnetic field, a current or a voltage, usually expressed in decibels

3.4

bandwidth (of a device)

width of a frequency band over which a given characteristic of an equipment or transmission channel does not differ from its reference value by more than a specified amount or ratio

[SOURCE: IEC 60050-161:1990, 161-06-09, modified – the note has been deleted.]

3.5

bandwidth (of an emission or signal)

width of the frequency band outside which the level of any spectral component does not exceed a specified percentage of a reference level

[SOURCE: IEC 60050-161:1990, 161-06-10]

3.6

bounded wave simulator

type of simulator for producing electromagnetic fields in a localized region of space referred to as a "test volume"

3.7

box

enclosure that contains electrical equipment

Note 1 to entry: Such boxes usually contain modules of subsystems.

3.8

broadband

3.8.1

broadband

<emission> emission which has a bandwidth greater than that of a particular measuring apparatus or receiver

3.8.2

broadband device

device whose bandwidth is such that it is able to accept and process all the spectral components of a particular emission

[SOURCE: IEC 60050-161:1990, 161-06-12]

3.9

circuit

collection of interconnected electronics forming one or more closed paths

3.10

conductive point-of-entry

electrical wire or cable or other conductive object, such as a metal rod, which passes through the electromagnetic barrier

3.11

coupling

interaction of electromagnetic fields with electrical systems, whereby part of the energy of the field is transferred to the system

3.12

current injection test

test technique by which, through some external means, a current is forced to flow in a circuit at a desired location

Note 1 to entry: For EMP testing purposes, it is a process by which simulated EMP transient current pulses are introduced into a component, circuit or system to measure damage or upset thresholds.

3.13

cut-off frequency

<waveguide> lowest frequency for which there is no attenuation of the electromagnetic fields propagating in a lossless waveguide

Note 1 to entry: Below this frequency, the fields attenuate exponentially with distance along the waveguide.

3.14

dipole

straight antenna, usually fed in the center, that produces maximum radiation in a plane normal to its principal axis

3.15

direct drive

excitation of an electrical system by directly applying a voltage or current source (either transient or continuous wave) to system cables or surfaces as a means of simulating the effects of transient EM pulses

Note 1 to entry: See current injection test (3.12).

3.16

direct field penetration

penetration of the system shielding by the EM field

3.17

direction of propagation

direction of the electromagnetic plane-wave propagation vector k , which is perpendicular to the plane containing the vectors of the electric and the magnetic fields

3.18

electric field strength

E

magnitude of the electric field vector of an electromagnetic wave or of a field created by an electric charge distribution, measured in volt per meter

3.19

electromagnetic barrier shield

topologically closed surface made to prevent or limit EM fields and conducted transients from entering the enclosed space

Note 1 to entry: The barrier consists of the shield surface and PoE treatments and it encloses the protected volume.

3.20

electromagnetic disturbance

any electromagnetic phenomenon which may degrade the performance of a device, equipment or system, or adversely affect living or inert matter

[SOURCE: IEC 60050-161:1990, 161-01-05]

3.21

electromagnetic environment

totality of electromagnetic phenomena existing at a given location

[SOURCE: IEC 60050-161:1990, 161-01-01, modified – the note has been deleted.]

3.22

electromagnetic pulse

EMP

all types of electromagnetic fields produced by a nuclear explosion

Note 1 to entry: Electromagnetic pulse is also referred to as nuclear electromagnetic pulse (NEMP).

3.23

(electromagnetic) radiation

- a) phenomenon by which energy in the form of electromagnetic waves emanates from a source into space
- b) energy transferred through space in the form of electromagnetic waves

[SOURCE: IEC 60050-161:1990, 161-01-10, modified – the note has been deleted.]

3.24

electromagnetic topology

description of the interconnection of shields or electromagnetic barriers in a system that limit the EMP environment within the system

3.25

external coupling

process by which an incident electromagnetic field strikes the exterior portions of a conducting system enclosure and induces currents and charges

3.26

gasket

element, normally electrically conductive and flexible, used to seal an aperture in an enclosure

3.27

inside-to-out

test method where the transmitting antenna is placed inside and the receiving antenna is placed outside the shielded enclosure

3.28**hardening**

process of decreasing the vulnerability of a system or component by design techniques, for example by protecting against, or decoupling from, an undesirable external environment such as EMP

3.29**high-altitude electromagnetic pulse****HEMP**

electromagnetic pulse produced when a nuclear explosion occurs outside the earth's atmosphere, typically above an altitude of 30 km

3.30**hyperband**

spectrum of EM field with a band ratio greater than 10

3.31**impulse radiating antenna****IRA****half IRA****full IRA**

full IRA with a full parabolic dish or half IRA with a divided parabolic dish on a conducting ground plane and an impedance transformer from 50 Ω to 100 Ω

3.32**inside-to-out**

alternative test method where the receiving antenna is placed outside and the transmitting antenna is placed inside of the shielded enclosure

3.33**magnetic field strength*****H***

magnitude of the magnetic field vector of an electromagnetic wave, or the field produced by a current flowing in a wire, loop antenna, etc., measured in amperes per meter

3.34**outside-to-in**

conventional test method where the receiving antenna is placed inside and the transmitting antenna is placed outside of the shielded enclosure

3.35**overall shielding****global shielding**

protection of an entire entity by use of a single shielding enclosure or some practical equivalent, such as the protection of the contents of an entire building by shielding the entire building

3.36**penetration**

transfer of electromagnetic energy through an electromagnetic barrier from one volume to another

Note 1 to entry: This can occur by field diffusion through the barrier, by field leakage through apertures, and by electrical current passing through conductors connecting the two volumes (wires, cables, conduits, pipes, ducts, etc.).

3.37

point-of-entry

PoE

physical location (point/port) on the electromagnetic barrier, where EM energy may enter or exit a topological volume, unless an adequate PoE protective device is provided

Note 1 to entry: A PoE is not limited to a geometrical point. PoEs are classified as aperture PoEs or conductor PoEs according to the type of penetration. They are also classified as architectural, mechanical, structural or electrical PoEs according to the architectural engineering discipline in which they are usually encountered.

3.38

PoE protective device

PoE treatment

protective measure used to prevent or limit EM energy from entering a protected volume at a PoE

Note 1 to entry: Common PoE protective devices include waveguides below cut-off, closure plates for aperture PoEs, and filters and surge arresters on penetrating conductors.

3.39

protected volume

three-dimensional space enclosed by an electromagnetic barrier

3.40

pulse

abrupt variation of short duration of a physical quantity followed by a rapid return to the initial value

[SOURCE: IEC 60050-161:1990, 161-02-02]

3.41

radio frequency

RF

frequency of the electromagnetic spectrum that is between the audio frequency portion and the infrared portion

Note 1 to entry: Sometimes, audio frequencies are considered to be included as part of the RF spectrum.

3.42

penetrating field

field inside the shielded volume that may penetrate via shield imperfections

3.43

shielded enclosure

screened room

mesh or sheet metallic housing designed expressly for the purpose of separating electromagnetically the internal and external environment

[SOURCE: IEC 60050-161:1990, 161-04-37]

3.44

shielding degradation

general or localized reduction of electromagnetic shielding effectiveness as a result of openings, penetrations, wear, improper utilization, etc.

3.45**shielding effectiveness****SE**

measure of the reduction or attenuation in the electromagnetic field strength at a point in space caused by the insertion of a shield between the source and that point, usually expressed in decibels (dB)

3.46**skin effect**

tendency of alternating current to concentrate in the surface layer of a conductor, resulting in the effective resistance of the conductor increasing with frequency

3.47**system**

collection of equipment, subsystems, skilled personnel, and techniques capable of performing or supporting a defined operational role

Note 1 to entry: A complete system includes related facilities, equipment, subsystems, materials, services and personnel required for its operation to the degree that it can be considered self-sufficient within its operational or support environment

3.48**transient, adjective and noun**

pertaining to or designating a phenomenon or a quantity which varies between two consecutive steady states during a time interval short compared with the time-scale of interest

[SOURCE: IEC 60050-161:1990, 161-02-01]

3.49**protection device**

device providing protection to a conductive PoE

Note 1 to entry: It may, for example, consist of one or more of the following: a spark gap, a metal oxide varistor (MOV) or a filter. These devices are used to reduce the electrical disturbance which penetrates an electromagnetic barrier.

3.50**waveguide below cut-off**

waveguide whose primary purpose is to attenuate electromagnetic waves at frequencies below its lowest cut-off frequency, while at the same time providing a physical opening into a shielded enclosure

3.51**wire mesh**

connected wire fabric normally used for protection of apertures in an electromagnetic barrier

** 3.52****mechanical stirrer**

rotating reflector used to approximate the average fields in a given space 

4 HEMP test concepts**4.1 General**

A key aspect in HEMP protection is describing and using the electromagnetic shielding topology of the system. This amounts to locating and characterizing the various surfaces (or electromagnetic barriers) within the system enclosing regions (volumes) protected against HEMP. In real systems, openings shall be present in the shields for the normal operation and functioning of the equipment inside. These openings degrade the shielding, and if the degradation is too large, various types of HEMP protection devices shall be provided at these

penetration points in the shield. The location of the various penetration points and the types of protective devices determine the location and type of test to be conducted to verify the system shielding.

As an example, a hypothetical case of a building containing a highly shielded screen room is considered. Inside the screen room, it is assumed that there are several equipment enclosures, linked together by shielded cables and connectors. The first shielding surface in this system is the building enclosure. Depending on the type of building, this may or may not provide significant shielding for the interior volume. After energy penetration along inappropriately protected signal and power lines field penetration through apertures in the wall (including cracks and inappropriate joints) and diffusion through the wall are the main pathways for external energy to leak into the shielded room. Large apertures in the form of doors and windows, as well as conducting penetrations for electrical power and communications lines, may be present. Tests of these individual penetration mechanisms shall be required to evaluate the shielding provided by this enclosure.

Inside the building, the HEMP field is attenuated somewhat by the building walls or enclosure. Thus, the electrical disturbance experienced by the internal screen room is lower than that of the ambient external HEMP field. Because the internal shielded room is specifically designed to reduce the EM fields inside, it is expected that it will function properly – if the various protection devices applied to the shield penetrations are operational. Field penetration through cracks and joints in the walls, diffusion through the shield material and conductive penetrations along signal wires are the main pathways for energy to leak into the shielded room.

Inside the screen room, the conducting exteriors of the equipment housing and the shielded cables form the third barrier in this hypothetical system. As before, the EM energy is able to penetrate into these internal boxes by conductive penetrations, aperture penetrations and by diffusion. Moreover, energy penetration through braided cables and cable connectors may occur on the lines linking the various internal equipment enclosures.

Annex A describes test concepts for both conductive and radiated disturbances. In Clause 4, various methods are described for testing protective measures against the radiated HEMP environment only. These tests involve the direct generation of EM fields acting on equipment enclosures or shields, or the injection of current and charge onto shields to simulate the radiated field interaction to the structures. In the remainder of Clause 4, a brief introduction into the various HEMP test concepts and techniques for radiated field disturbances is given. The specific test procedures are presented in Clause 5.

4.2 Testing of shielding enclosures

4.2.1 General

There are several different ways of characterizing the behaviour of protective enclosures. Below, various test concepts are examined that serve to describe the shielding behaviour of the individual shielding elements in question. Annex A should be consulted for more information regarding these types of HEMP tests. Instead, test methods for verifying the protection levels provided by individual shielding components within the system will be examined and indication given as to what should be measured in the tests.

Field transfer functions

A common measure of shielding is obtained by examining the strength of the internal EM field relative to the intensity of the external excitation EM field (i.e. the field with the building removed). Because the external and internal EM environments can be defined in terms of either the *E*-field or the *H*-field, and because these fields are vector quantities, a large number of field combinations is possible. Moreover, these fields are time-varying in nature, due to the transient nature of the HEMP threat.

Considering the internal and external fields to be decomposed into their frequency-domain spectra, a measure of the attenuation provided by the building is provided by the field transfer function $T(\omega)$ which is the ratio of suitably chosen field quantities as

$$T(\omega) = \frac{A_{\text{in}}(\omega)}{A_{\text{out}}(\omega)} \quad (1)$$

where

$A_{\text{out}}(\omega)$ represents the spectral magnitude and phase components of a particular vector component of either the E or H excitation field outside the facility; and

$A_{\text{in}}(\omega)$ represents a magnitude and phase component of either E or H inside the building.

Depending on the choice of the internal and external fields, this ratio can be dimensionless or have dimensions of an impedance (in ohms) or an admittance (in siemens).

The field transfer function in Equation (1) is a complex valued function, having both a magnitude and phase. An illustration of a measured transfer function between the external excitation and the internal H -fields for a sample shielding enclosure is illustrated in Figure 1. If an accurate representation of the internal transient fields is to be determined from measurements of $T(\omega)$, both quantities shall be measured. If only a relative indication of the attenuation as a function of the frequency is desired for the building, then it is sufficient to measure only the magnitude $|A_{\text{in}}|$ and $|A_{\text{out}}|$.

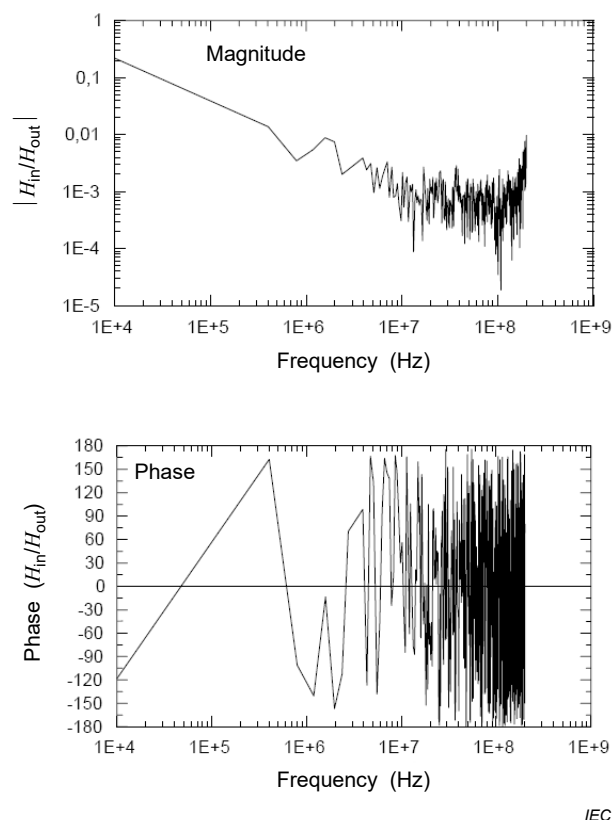


Figure 1 – Example of measured magnitude and phase of the transfer function $T(\omega) = H_{\text{in}}/H_{\text{out}}$ for a shielded enclosure

Shielding effectiveness

The shielding effectiveness of a facility is closely related to the shield transfer function discussed above in that it compares the relative magnitudes of two similar field components in

the frequency domain. However, this quantity contains less information because the phase information is lacking. Shielding effectiveness of the enclosure is defined as follows:

$$SE_A = 20 \log_{10} \left(\frac{|A_{out}|}{|A_{in}|} \right) = 20 \log_{10} \left(\frac{1}{|T_A(\omega)|} \right) \text{ dB} \quad (2)$$

where

A_{out} and A_{in} represent suitable external and internal E - or H -field quantities.

Thus, it is closely related to the magnitude plot of the transfer function for the fields.

Because of the fundamental differences in electric and magnetic shielding mechanisms at low frequencies, the shielding effectiveness for electric fields, denoted by SE_E , and for magnetic fields, SE_H , are significantly different at low frequencies. Figure 2 illustrates the theoretical shielding provided by a closed aluminum shell of a thickness of 0,5 mm. Generally, SE_H is less than SE_E at low frequencies (below 100 kHz), due to the fact that the low-frequency magnetic field is able to diffuse through the protective enclosure walls more easily than does the electric field. It is for this reason that magnetic field SE is typically used at lower frequencies (below 10 MHz), and at higher frequencies (above 10 MHz) the SE for electric or magnetic field can be used to characterize an enclosure.

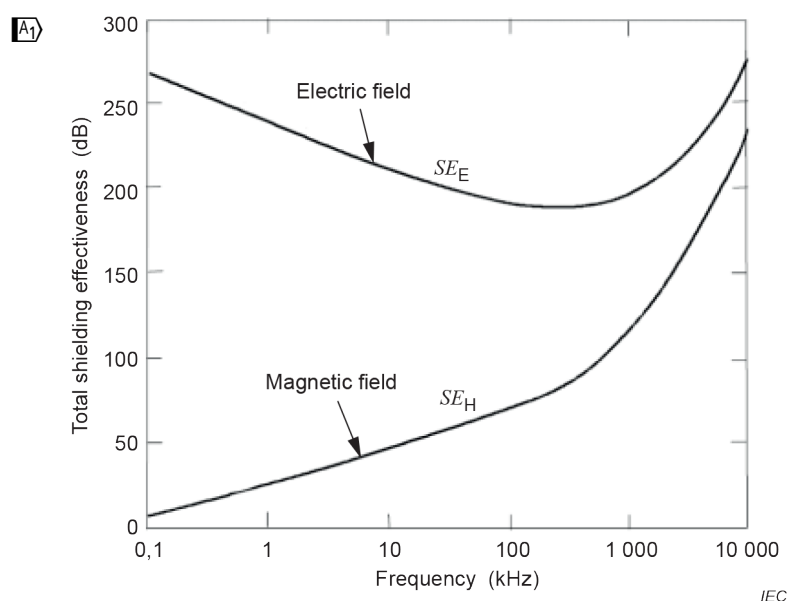
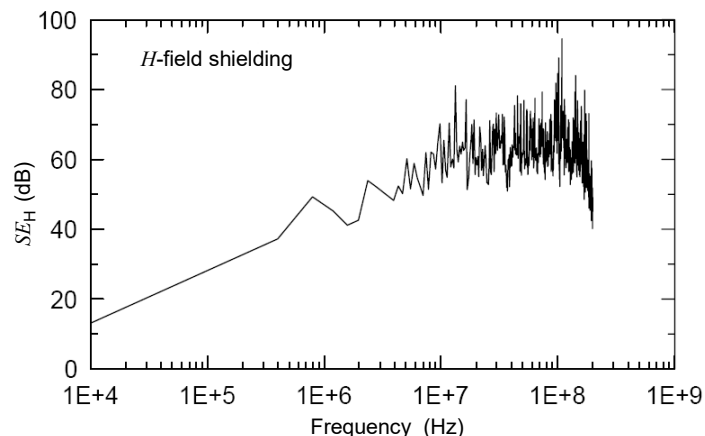


Figure 2 – Electric field and magnetic field shielding effectiveness of a 0,5 mm thick aluminium enclosure [29]¹

As a further example of the measured magnetic field shielding effectiveness of a real enclosure, Figure 3 illustrates the behaviour of SE_H as measured for the same building discussed in Figure 1. It should be noted that the shielding has several peaks and nulls, corresponding to internal and external resonances of the enclosure, as well as frequency-dependent penetrations that occur in addition to the simple diffusive penetration of fields through the shield material.

¹ Numbers in square brackets refer to the Bibliography.



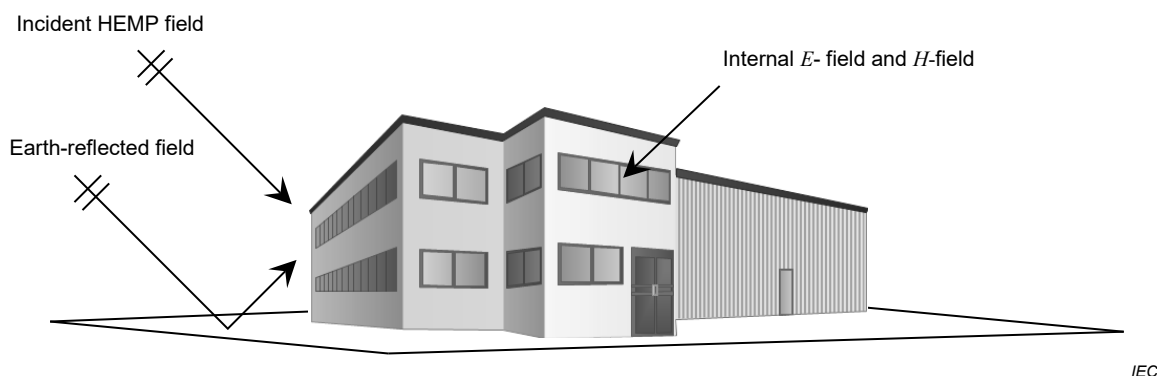
IEC

Figure 3 – Measured magnetic field shielding effectiveness SE_H for a building

4.2.2 Buildings

For a building such as that illustrated in Figure 4, the internal HEMP-induced response arises mainly from conductive and aperture-type penetrations. Thus, any test of the global enclosure shielding should strive to adequately excite these penetrations. The field penetration by diffusion through the building shield (i.e. the walls of the enclosure) is generally smaller than that of the conducting shield inside the walls.

The HEMP test concept for physically large buildings requires either the excitation by HPEM ultra-wideband (UWB), continuous wave (CW) signals simulating fields on the exterior of the test object (see the discussion of the various test interface locations in Figure A.1). For this excitation, the measurement of a suitable internal response induced by this external field is needed.



IEC

Figure 4 – Conceptual illustration of the HEMP test of a building

On the exterior of the building, the radiated or simulated HEMP excitation field is expressed by the following parameters (see IEC 61000-2-9):

- the incident field (plus ground-reflected field, if any) waveform characteristics (such as its amplitude, rise time, and fall time);
- the excitation field polarization;
- the amount of the system exterior illuminated by the radiated or simulated field.

Details of how this external field may be produced or approximated are presented in 5.2.

Different types of internal responses can be chosen to describe the shielding of the facility enclosure. These include the internal E - or H -fields or the induced voltage and current on internal conductors. Consequently, different measures for the shielding can be generated for any particular system. Moreover, the location of the internal observation point can vary, again giving rise to wide variations of shielding figures of merit.

4.2.3 Shelters and shielded rooms

For a shelter or a shielded room, it is assumed that the radiated HEMP environment is still being applied to the exterior of the enclosure where the incident HEMP fields are assumed to provide the main excitation to the structure. Consequently, the test concepts for these enclosures are similar to those for large buildings. These smaller enclosures can again be characterized by either

- a complex-valued field transfer function, or
- a shielding effectiveness.

It should be kept in mind, however, that there will also be transient signals conducted into this facility on conducting PoEs such as power lines and data lines, and these shall be addressed separately, as discussed in IEC 61000-5-3.

The main difference between large buildings without conducting shielded enclosures and shelters or shielded rooms is that the HEMP protection levels provided by these smaller enclosures will be significantly higher, since they are specifically designed to provide a high degree of shielding. Consequently, the internal signal levels are usually smaller than in the case of just buildings. This makes the measurements more susceptible to noise. In addition, due to the smaller size, the effects of internal cavity resonances will occur at higher frequencies. As a result, quasi-static shielding concepts are applicable over a wider range of frequencies for these enclosures (see IEC 61000-5-3).

Figure 5 illustrates a generic shielded room with several PoEs of the shielding barrier identified.

NOTE Power and signal conducting penetrations are not illustrated, as they are considered separately in IEC 61000-4-25.

Characterizing the overall barrier shielding by a field transfer function $T(\omega)$, or by shielding effectiveness SE , provides a global measure of the penetration effects from all of the penetration mechanisms indicated in Figure 5. That is to say, the internal fields arise from the penetrations from all of the PoEs taken together, along with the diffusion through the material in the walls of the shield. Other measurement techniques are available for characterizing the protection provided by the individual penetrations (such as the gasket, air vent, shielded conduit, etc.) and these are discussed in 4.4.

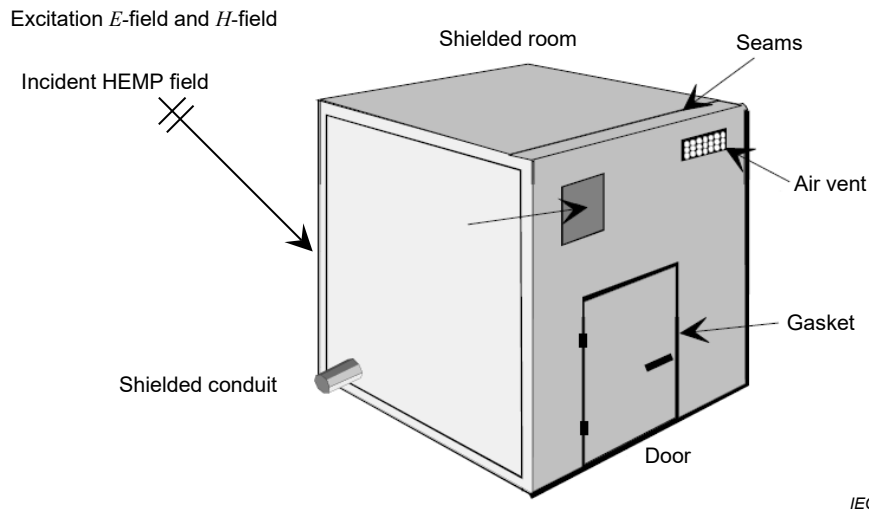


Figure 5 – Illustration of a shielded room or enclosure excited by HEMP fields

4.2.4 Cabinets, racks and boxes

These enclosures are typically located within an existing EM barrier, which significantly modifies the electromagnetic field environment exciting the system. An internal box or an equipment cabinet is excited by a combination of the internal EM field plus injected currents on cable shields coming from other equipment that have also been excited by the local fields. This is illustrated in Figure 6.

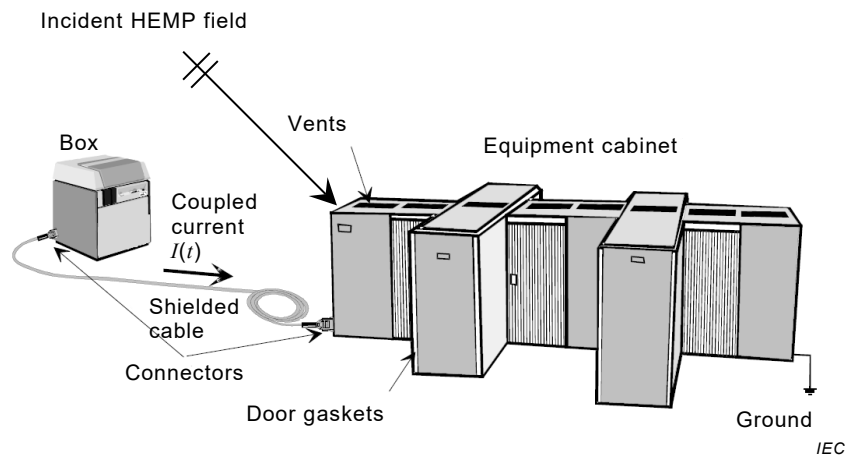


Figure 6 – Illustration of equipment racks, cabinets and box excited by internal HEMP disturbance

Field illumination test

For tests of these enclosures involving the EM fields inside a larger enclosure, the previous concept of field illumination can be adopted to measure the global shielding provided by the equipment. As before, this shielding may be characterized by

- a complex-valued field transfer function, or
- a shielding effectiveness of the enclosure.

Due to the smaller size of these enclosures, however, difficulties in this measurement can arise from the dense internal packing of internal electronic components. Often this makes it difficult to locate suitable EM field sensors inside the box. Furthermore, because the testing is conducted on the box or enclosure surface, there are large uncertainties in the

characterization of the HEMP field environment. Finally, the interconnection between the various equipment items can be rather complex, and if a single box or equipment rack is tested, its measured response may be considerably different from that found when it is connected to the rest of the system.

Shield transfer impedance

An alternative to the field testing of boxes and small enclosures is to use the concept of a transfer impedance of the enclosure (see Annex E). This is similar to the treatment of a shielded cable discussed in 5.3, and involves testing at a box level interface in the system. In this case, a current $I(t)$ is injected onto the surface of the box or rack, and an open-circuit voltage $V_{oc}(t)$ on a suitable internal sense wire is measured. In this form of testing, it is important to ensure that the injected current flows over the exterior of the box in the same way as when the box is connected to the rest of the system. This implies that the current exit point (the ground connection) has to be maintained so that the injected current can be removed properly.

Figure 7 illustrates a general shielded enclosure excited by an external current injection. Just inside the shell at points a and b, a sense wire is connected to the shield, and the open-circuit voltage V_{oc} is measured. The transfer impedance of this enclosure is a complex valued quantity, defined in terms of the frequency domain spectral components as

$$Z_t(\omega) = \frac{V_{oc}(\omega)}{I(\omega)} \quad (3)$$

where

$I(\omega)$ is the injected current, and

$V_{oc}(\omega)$ is the measured open-circuit voltage on the sense wire.

This shield transfer impedance value varies, depending on the location of terminals inside the enclosure for determining the open-circuit voltage. For adequate sensing of the shielding provided by the entire enclosure, the voltage sense points should be located within the enclosure, near the current injection locations.

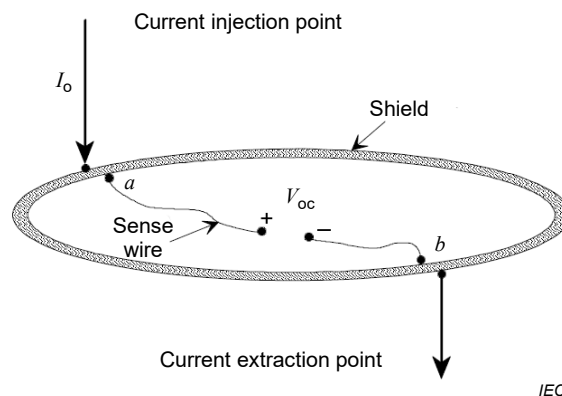


Figure 7 – A general shield excited by current injection

The shield transfer impedance is a function of the electrical properties of the shielding material, as well as the shield dimensions and the nature of any imperfections in the enclosure such as seams, apertures, etc. In the special case of a thin spherical shield in which there are no aperture penetrations, it is possible to calculate the H -field shielding effectiveness SE_H , given the shield transfer impedance and the d.c. resistance of the shield through the relationship:

$$SE_H = 20 \log_{10} \left| \frac{\left(\frac{a}{\Delta} (\gamma \Delta)^2 \right)}{3 \frac{Z_t}{R'}} \right| \quad (4)$$

where

a is the radius of a thin spherical shield (in m);

Δ is the thickness of the shield (in m);

γ is the propagation constant in the shielding material, given by $\gamma \approx \sqrt{j\omega\mu\sigma}$;

σ is the electrical conductivity of the shield material (in S/m);

Z_t is the shield transfer impedance (in Ω/m);

R' is the per unit length d.c. resistance of the shield (in Ω/m).

4.3 Testing of shielded cables and connectors

4.3.1 General

Shielded cables are frequently used to transmit information between equipment contained within two protective enclosures. As such, one can define two distinct transmission lines: an external line having currents and charges flowing on the exterior of the cable, together with a possible ground-plane return, and an internal line consisting of the conductors inside the shield. HEMP fields can excite the external transmission line, and if the cable shield is imperfect, some of the external currents and charges can penetrate through the shield and excite the internal line. This leads to an unwanted response in the "protected" equipment. In 4.3, test concepts for this coupling mechanism are examined.

Annex B summarizes important aspects of the characterization of a cable shield. This involves two parameters: the shield transfer impedance and the transfer admittance. For most practical cable shields, the transfer impedance is a complex valued, frequency-dependent function, described by real and imaginary parts, or equivalently, by a magnitude and phase function. The transfer admittance, however, is primarily reactive, and is effectively modelled by a frequency independent capacitance.

While the transfer impedance is a function of the shield properties only, the transfer admittance depends on both the shield and the configuration of the external transmission line. It is possible, however, to present the measured transfer admittance parameter in another form: that of the shielding leakage parameter, which is independent of the external circuit. Subclause 4.3.2 considers test methods for the transfer impedance and admittance quantities, keeping in mind that the latter quantity depends on the details of the external circuit, such as the external line height, wire radius, and nature of the local ground plane near the cable.

4.3.2 Testing of cable shields

4.3.2.1 Determination of the transfer impedance

Although there are several different test configurations for measuring the transfer impedance of a cable shield, they are all related to the basic configuration shown in Figure 8. An external voltage source V_s feeds the $x = 0$ end of a cable shield of length L which is connected to the ground (i.e. the reference conductor) through a short-circuit at the opposite end of the cable. The resistance Z_s at the source limits the current flowing in the cable exterior.

The inner (coaxial) conductor of the shielded cable is shorted to the shield at the $x = L$ end of the line, and the open-circuit voltage, V_i , is measured at the $x = 0$ end. Under the assumptions that

- the internal and external transmission lines are electrically short ($L \ll \lambda$), and

- that there is negligible field excitation of the inner cable due to fields entering through the ends of the line,

the frequency-dependent transfer impedance of this cable shield can be approximated from Equation (B.8) as

$$Z'_t(\omega) = R'_t(\omega) + jX'_t(\omega) \approx \frac{V_i}{I_e L} \approx \frac{Z_s}{L} \frac{V_i}{V_s} \Omega/\text{m} \quad (5)$$

where

Z'_t is the cable transfer impedance (in Ω/m);

ω is the angular frequency (in $2\pi \times \text{Hz}$);

V_i is the open-circuit voltage on the internal conductor;

I_e is the open-circuit current on the shield;

V_s is the excitation voltage of the external circuit of the cable shield (in V);

L is the length of the shield conductor (in m);

Z_s is the effective source impedance of the external voltage source (in Ω).

When using these expressions, it is very important to ensure that the line is electrically short. As the frequency increases, the current distribution on the exterior cable begins to have periodic nulls and peaks due to reflections from the shorted end of the line. Moreover, there are internal reflections from the short on the interior cable. These oscillations are the cause of significant errors in the measurement of transfer impedance at high frequencies.

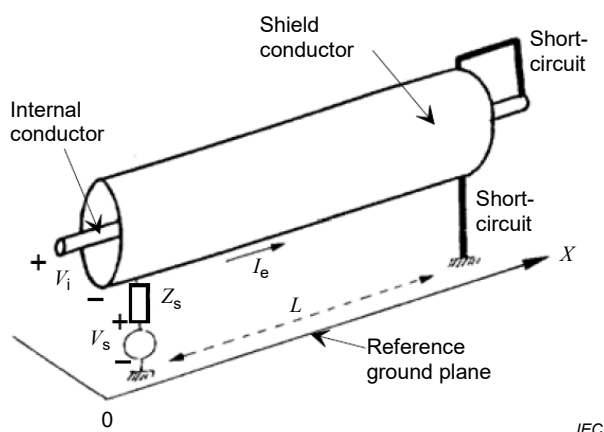
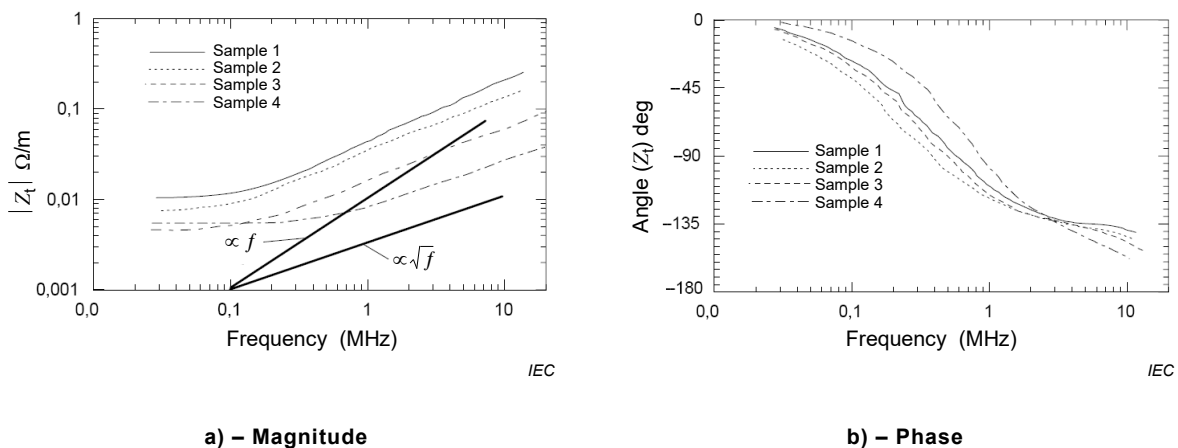


Figure 8 – Basic configuration for transfer impedance measurement

Figure 8 illustrates the typical frequency domain behaviour of the measured transfer impedance for four different braided cables having reasonably good shielding. At low frequencies, Z'_t is primarily resistive, with a value equal to the per-unit-length d.c. resistance of the shield. At higher frequencies, the field penetration through the apertures in the braid of the shield begins to affect the internal response and the shielding behaviour is slightly degraded. Accompanying this increase in transfer impedance at high frequencies is an electrical phase variation – a quantity that it is essential to know if any detailed calculations are to be performed using the measured Z'_t .



NOTE At high frequencies the curves are proportional to $\sqrt{f}$ rather than f , which indicates that responses are not well represented by a simple inductance.

Figure 9 – Measured transfer impedance magnitude and phase of transfer impedance per unit length for four braided shield cables with good shielding properties

4.3.2.2 Determination of the transfer admittance

The evaluation of the transfer admittance of the cable shield utilizes the general test configuration shown in Figure 10. This is similar to the configuration for the transfer impedance measurements, but with different terminations at the cable ends. Using Equation (B.9), together with the same assumptions as for the transfer impedance, the transfer admittance of the shield can be expressed as

$$Y_t' \approx -\frac{1}{L} \frac{I_i}{V_s} \approx -j\omega C_i' C_e' S \text{ S/m} \quad (6)$$

where

Y_t' is the cable transfer admittance (in S/m);

I_i is the internal conductor current (in A);

V_s is the excitation voltage of the external circuit of the cable shield (in V);

L is the length of the cable (in m);

ω is the angular frequency (in $2\pi \times \text{Hz}$);

S is the shield leakage parameter (in m/F);

C_i' is the internal per-unit-length capacitance of the coaxial cable (in F/m);

C_e' is the external per-unit-length capacitance of the coaxial cable (in F/m).

Thus, a measurement of the internal conductor current arising from the external source voltage provides the transfer admittance. Under the approximation that Y_t' is purely reactive, the shield leakage parameter can be determined, if the internal and external per-unit-length capacitances of the coaxial cable are known. The parameter S is a single, real-valued number, and depends only on the characteristics of the braided cable. Hence, it is a useful descriptor for cable shields.

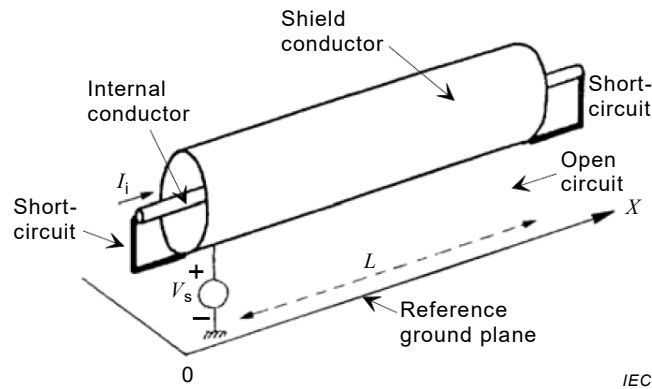


Figure 10 – Basic configuration for transfer admittance measurement

4.3.3 Testing of cable connectors

Connectors on shielded cables are often more important in determining the overall shielding of the cable system than is the cable shield. This is because the connector introduces an interruption to the shield, and, as such, presents an imperfection in the shielding topology. One way to represent the effects of the connector (as seen by the internal, or shielded, transmission line circuit) is by using discrete voltage and current sources at the location of the connector. The strengths of these sources are related to the external current and voltage on the connector multiplied by discrete transfer impedance and admittance parameters representing the connector, much as in the case of the distributed cable shield penetrations.

As in the case of a braided shield, the lumped transfer impedance of a connector contains both a resistive and reactive part, and the transfer admittance of a connector is primarily capacitive. However, cable connectors are always designed so that there is very small E -field penetration through the device. Consequently, the transfer admittance effects of the connector are almost always much lower than the effects from the transfer impedance. Usually, the lumped transfer impedance parameter is the only one required.

The test configuration for cable connectors is similar to that for the cable shield transfer impedance discussed previously. Figure 11 illustrates the general test configuration for such measurements. The same requirements for the test equipment for the cable shield test are required here, and the construction of the outer shield shall be such that it is a much better shield than the connector. This implies that a solid shield is preferable to a braided shield for this measurement.

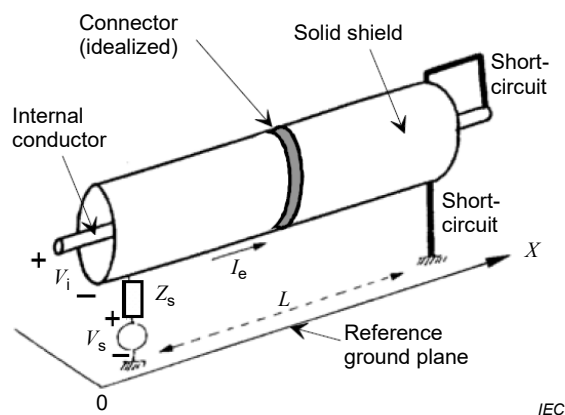


Figure 11 – Test configuration for transfer impedance measurement of a cable connector

Given a measurement of the internal open-circuit voltage, the transfer impedance of the connector is determined by the expression

$$Z_t(\omega) = R_t(\omega) + jX_t(\omega) \approx \frac{V_i}{I_e} \approx Z_s \frac{V_i}{V_s} \Omega \quad (7)$$

where

V_i and V_s have been defined in 4.3.2.1,

Z_t is the transfer impedance of the connector (in Ω), and

Z_s is the impedance of the external circuit (in Ω).

It should be noted that while the length of the cable, L , does not appear explicitly in this expression, it is necessary that $L \ll \lambda$. Thus L should be as short as possible to maximize the frequency range of validity for the measurements.

4.4 Testing of shielding materials

4.4.1 General

Imperfections in the shielding topology of a system can often be protected by using localized methods such as gaskets (on seam or between doors and their jambs), conducting sheets or screens (covering apertures), and other specialized measures like honeycombs and waveguides beyond cut-off. Characterizing these protection measures is less obvious because their behaviour depends not only on their individual electrical composition, but also on how the devices are connected to the shielding topology. For example, a very long crack might be protected by filling it with a conducting material. This could be effective in protecting against currents flowing across the crack: the conducting material lets the current pass over the crack without much distortion and the H -field on the shielded side is minimized. However, for currents parallel to the crack, the presence or absence of the protective filling is unimportant. The current is not significantly affected by the slit, and any protection against this current component is unnecessary.

In describing tests suitable for these components, therefore, an attempt is made to characterize the intrinsic shielding property of the protection device, independently of how it is used in a particular installation. This means that a particular component might be classified as a "good" protective device in one installation, but due to the particularities of how it is used in another facility, considered to be a "poor" component in another installation. Evaluating the global behaviour of a system, together with all of its protection devices, is the role of system level testing, a subject which is beyond the scope of this standard.

4.4.2 Conducting gaskets

Figure 12 shows several configurations of a conducting gasket serving as a HEMP protection device. The basic mechanism for protection is that the gasket forms a conducting path between the two parts of the enclosure; this keeps current and charge from "leaking" into the inside (i.e. into the protected region). Each of the three configurations in the figure has a different shielding behaviour, due to the differences in the geometry of the enclosure walls that surround the gasket.

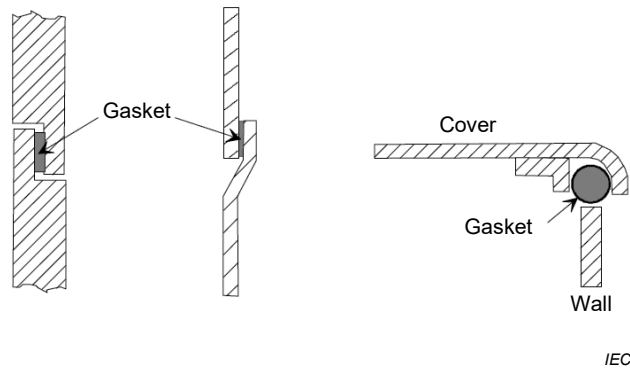


Figure 12 – Examples of conducting gaskets used as HEMP protection devices

A simple yet general circuit model for a gasket seal can be made by noting the important parts of the geometry in Figure 12. Current flowing from one conductor to another has to pass through the gasket and this will present an electrical resistance to the current. Similarly, the flat plates on either side of the gasket appear locally as a capacitance through which a displacement current can flow. Finally, the metal conductors of the two walls form an inductance in this circuit.

Figure 13 shows the equivalent circuit representation of such a gasketed opening. The resistance of the gasket and the capacitance of the gasket opening appear in parallel, and this combination is in series with the inductances representing the current paths through the walls of the enclosure. Specific values for L and C depend on the local geometry of the seal, whereas the value of R depends on both the geometry and on the intrinsic electrical properties of the gasket material.

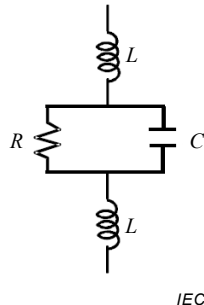


Figure 13 – Circuit model representing the behaviour of a conducting gasket for HEMP protection

These circuit values can be measured or calculated using simple models for the specific shape and geometry under consideration for a given problem. For characterizing the electrical properties of the gasket material, however, measurements of electrical resistivity of the gasket material can be used. This quantity is independent of the surroundings of the gasket and can be used to rank the effectiveness of one type of gasket with another. It should be noted, however, that such gaskets are usually made of flexible material, and, therefore, their characteristics are dependent on contact pressure as in all examples of Figure 12. The age of gasket materials is also a factor.

Figure 14 illustrates the measurement configuration for the resistivity. This is the four-electrode method, and it is specially designed so that measurements of materials with very low resistivities can be made. For this measurement, a block of the gasket material is sandwiched between two electrodes made from copper or another highly conducting material. An external d.c. voltage source is connected across the two outer electrodes and a current is allowed to pass through the electrode. The resulting voltage drop across the sample is measured using a high input impedance voltmeter, so as not to disturb the current flow in the

sample. With these parameters measured, the d.c. resistivity of the sample material is given by the expression:

$$\rho_{DC} = \frac{V_s}{I_o} \frac{A}{L} \quad \Omega \cdot m \quad (8)$$

where

ρ_{DC} is the d.c. resistivity of the sample material in ($\Omega \cdot m$);

A is the cross-sectional area of the gasket material (in m^2);

L is the thickness of the gasket sample (in m);

I_o is the current passing through the sample (in A);

V_s is the voltage drop across the sample (in V).

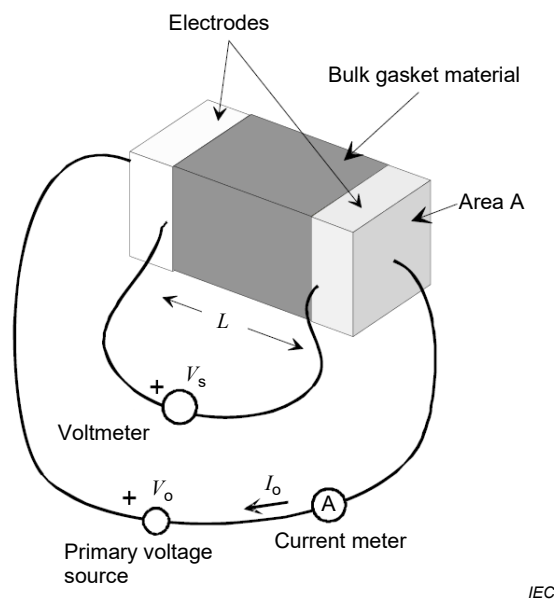


Figure 14 – Measurement configuration for the resistivity of a sample

Similar measurements can be made at higher frequencies and a frequency-dependent gasket impedance can be measured. However, this quantity is of limited use, because its frequency variations are easily confused with those of the gasket-mounting hardware and surroundings. Consequently, the d.c. resistivity is the most commonly used parameter for characterizing the gasket material.

4.4.3 Conducting sheets and screens

4.4.3.1 General

Conducting screens or sheets of conducting material are often used to limit the HEMP penetration through apertures in the shield. Such protection devices include

- wire mesh screens;
- conductive paint coatings;
- vacuum metallized coatings;
- flame/arc sprays;
- metallic foils lining equipment bays;
- metallic fillings added to plastic enclosures.

As in the case of gasketing material, it is possible to characterize these protection devices either by measurements of their shielding behaviour as installed in a specific topological configuration, or by an alternate measurement of some intrinsic electrical property of the shielding material. While this latter measurement may not accurately indicate how the protection device will function in an arbitrary installation, it does provide a useful technique for distinguishing between one protection material and another in a self-consistent manner. Two test concepts for conducting aperture protective devices are discussed in 4.4.3.2 and 4.4.3.3: one which measures the resistivity of the conducting material, and another which measures the shielding effectiveness of the material used for shielding under controlled conditions.

4.4.3.2 Measurement of material resistivity

The resistivity of the material comprising the protective cover of an aperture is one parameter that may be used to characterize its shielding. As in the case of the conducting gasket described in 4.4.2, the resistivity of a conducting sheet can be determined using the test configuration shown in Figure 14. An alternative approach is to use a measurement technique in which the d.c. resistivity is measured with probes located on the surface of the sample as indicated in Figure 15.

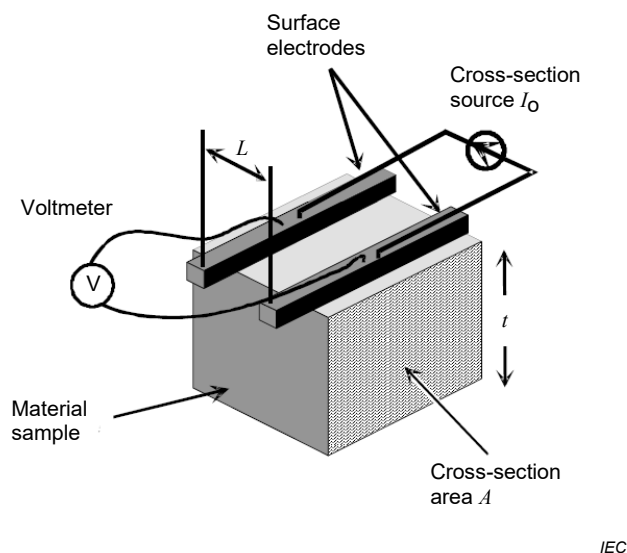


Figure 15 – Test concept for measuring the resistivity with surface probes

In this test, a constant d.c. current source I_0 is connected to two electrodes separated by a distance L and in good electrical contact with a block of conducting material. In response to this current, a voltage V_s is induced across the two electrodes. This voltage may be measured by a high impedance voltmeter and the resistivity is again given by the expression in Equation (8). The same expression is used in the present case, because it is assumed that the block is a good conductor and the current tends to flow uniformly across the cross-sectional area A of the material from one electrode to the other.

It is important to note that this measurement procedure is applicable only at low frequencies where the skin depth of the material in question is very large compared to the thickness of the sample. If the frequency of the current source were allowed to increase, the skin depth (given by $\delta = \sqrt{\rho/(\pi f \mu)}$) decreases and, at some point, begins to be comparable with the thickness of the material under test. At this point, the details of the current distribution in the conductor cross-section shall be taken into account, as discussed in Annex E.

As noted in Annex E, both the surface impedance (relating the tangential E -field outside the protective barrier to the excitation surface current) and the transfer impedance (relating the tangential E -field inside the protective barrier to the excitation surface current) may be calculated (see Equations (E.14) and (E.18)), once the material resistivity is known. Thus, the

d.c. measurement of the resistivity can be used to infer the shielding properties of the material for higher frequencies.

4.4.3.3 Shielding effectiveness measurements

A more direct approach for characterizing the shielding behaviour of a wire mesh or conducting screen is to measure its shielding effectiveness under standard conditions. It is well known that in the near field (or equivalently, for low frequencies), the electric and magnetic fields penetrate into a conductor differently. Consequently, a shield shall be characterized in general by two different shielding effectiveness parameters. For far-field shielding, where the incident field on the shield is a plane wave, the two shielding effectiveness values become equal, and this single value may be used to characterize the protection.

Figure 15 illustrates a measurement concept for the plane-wave shielding effectiveness of screens and sheets. Figure 15 a) shows the ideal situation, in which a plane wave is incident upon an infinite screen. The shielding of this screen can be characterized by the following equation (see Equation (2)):

$$SE_A = 20 \log_{10} \left(\frac{|A_{out}|}{|A_{in}|} \right) \text{ dB} \quad (9)$$

where

A_{out} represents the principal component of the incident field E^{inc} (or H^{inc}) at an observation point with the conducting screen removed;

A_{in} is the same component of the field that is transmitted through the screen: E^{tr} (or H^{tr}).

The resulting shielding effectiveness depends on the angle ψ that the incident field makes with the normal to the sheet. Normally, the angle $\psi = 0^\circ$ is chosen for defining the shielding properties of the infinite plane.

For actual measurements, the idealized configuration of Figure 16a) cannot be realized, due to the fact that the source producing the incident field is not of infinite size, nor is it infinitely far from the screen. Moreover, the screen is not infinitely large. This implies that the measurements made using the test configuration in Figure 16b) can be different from those expected from a theoretical treatment of the infinite plane geometry, due to the following effects:

- the non-plane-wave nature of the incident fields from the source;
- the radiation pattern from the source;
- diffraction from the edges of the screen.

To minimize this difficulty, it is common to require the following conditions to be maintained in the measurement configuration:

- the size of the screen $a \gg \lambda$;
- the observation and source positions d_o and $d_s < a$;
- $\psi = 0^\circ$ (normal incidence).

With these assumptions, an approximation to the plane-wave shielding effectiveness of the screen is obtained by making two measurements of the selected primary field components at the observation location. The first measurement is with the plate removed and is denoted as $E_{removed}^m$ (or $H_{removed}^m$). The second measurement is the same field component with the plate

in place in front of the radiator, and is denoted as E_{covered}^m (or H_{covered}^m). The shielding effectiveness for this configuration is then evaluated as

$$SE = 20 \log_{10} \left(\frac{|E_{\text{removed}}^m|}{|E_{\text{covered}}^m|} \right) \text{ dB} \quad (10)$$

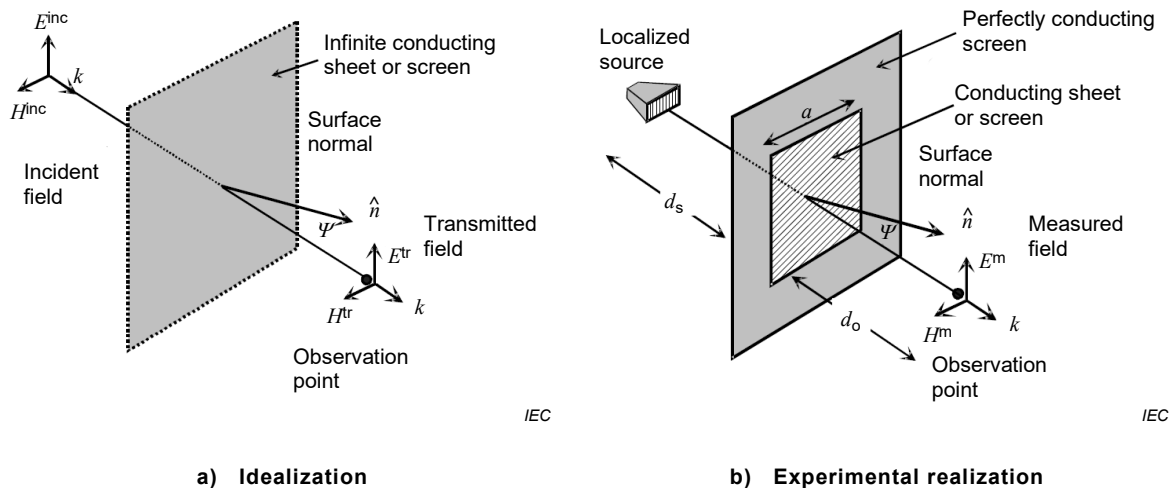


Figure 16 – Concepts for shielding effectiveness measurement of conducting sheets and screens

As an example of the plane-wave shielding effectiveness of a plate of different material, Figure 17 presents calculated data for copper, aluminium and iron sheets, each having a thickness of 0,01 mm. Similar results are expected for materials having other conductivities.

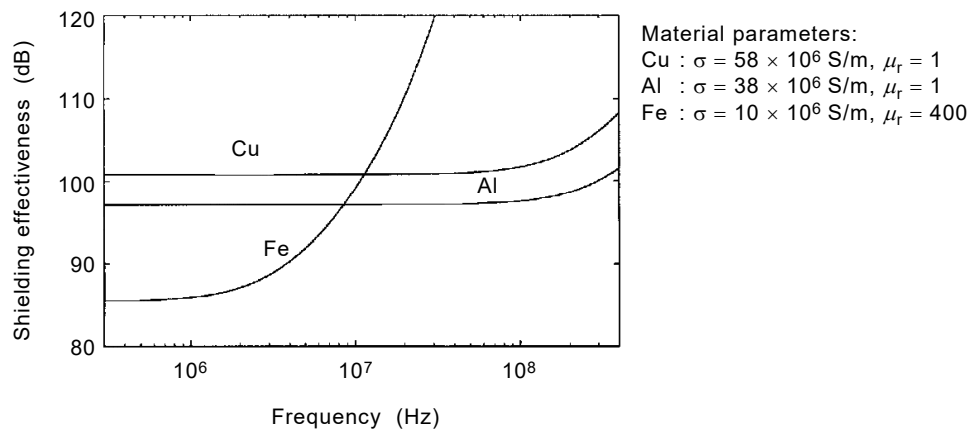


Figure 17 – Example of the calculated plane-wave shielding effectiveness of a 0,01 mm thick plate of different material as a function of frequency

4.4.4 Cut-off waveguides and honeycombs

Another type of HEMP protection measure is to use one or more cut-off waveguides or honeycomb structures in a conducting wall, as illustrated in Figure 18. This permits the easy flow of air or other non-conducting material in and out of an enclosure, while at the same time providing large attenuation to the EM field environment. The test concept for this penetration protection method is identical to that for the conducting mesh or screen shown in Figure 15.

As before, the waveguides or honeycomb protection shall be located in a highly conducting wall, and shielding effectiveness measurements shall be made with and without the wall present, as described in 4.4.3.

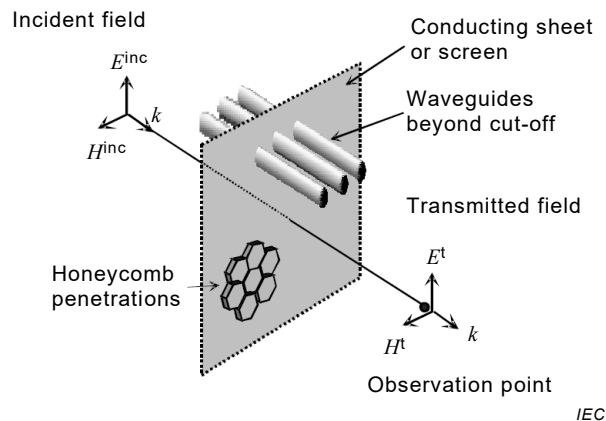


Figure 18 – Cut-off waveguides and honeycomb used as protective elements

4.5 Summary of test concepts

A number of different test concepts have been presented in Clause 4 for different aspects of shielded systems. Table 1 summarizes the recommended test concepts for the different system components. In selecting the various tests, it is important to realize that there is never a "best" test for a system. Each test has its strong points and its flaws. Each test has uncertainties and errors in the result, for example test object and measurement equipment interaction, test object variability, uniformity of fields, non-linear effects and measurement errors. In selecting a test, therefore, the user should carefully consider the following requirements for the proposed test:

- why is the test being conducted?
- is the test really necessary?
- what is the expected result from the test?
- what is the required accuracy of the test results?

Answers to these questions will serve to put the various test procedures into better perspective and will allow the user to select the proper test and minimize the cost of the testing.