



IEEE Guide for the Characterization of the Shielding Effectiveness of Planar Materials

IEEE Electromagnetic Compatibility Society

Developed by the
Standards Development Committee

IEEE Std 2715™-2023

STANDARDS

IEEE Guide for the Characterization of the Shielding Effectiveness of Planar Materials

Developed by the

Standards Development Committee
of the
IEEE Electromagnetic Compatibility Society

Approved 15 February 2023

IEEE SA Standards Board

Abstract: A set of standard methods and procedures for determining the shielding effectiveness of planar materials is provided. Such materials might comprise, but are not limited to, metals, coated plastics, fiber-filled polymers, textiles, and coated fabrics. The selection of the appropriate test method to determine the level of shielding provided in the intended application, to provide a basis for comparing the measuring results, is considered. Emphasis is placed on those measurement techniques that have been adopted through incorporation into standards, both commercial and military, or that have been used extensively in practice.

Keywords: electromagnetic shielding, IEEE 2715™, measurement techniques, nested reverberation room, planar materials, reverberation chamber, shielding effectiveness, TEM cell, transverse electromagnetic cell

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Introduction

This introduction is not part of IEEE Std 2715-2023, IEEE Guide for the Characterization of the Shielding Effectiveness of Planar Materials.

A shielding material is a conductive material used to make shielded enclosures, to shield against incoming electromagnetic (EM) fields regarding immunity, and to reduce the emission of EM waves by the circuit or system. For most applications, the choice of the material intended for designing and manufacturing the shielded enclosure is based on the characterization of planar samples of the shielding material. It should be clearly stated that the final shielding result regarding the enclosure depends not only on the choice of the shielding material, but also on the way of assembling parts of the enclosure, openings, and cable entries. Several techniques are available to measure the shielding properties of materials. Unfortunately, measurement results are often inconsistent between techniques. A table summarizing the different methods and their main characteristics is provided in [Annex A](#).

This guide provides guidance on the use of recognized techniques for the measurement of the shielding effectiveness (SE) of planar materials, depending on the boundary conditions of each technique. It does not recommend one technique over another. It is also recognized that some of the “alternative” techniques may, in the future, become widely accepted and practiced. At such time, the guide will be revised to reflect their adoption. It is also recognized that efforts are currently underway to revise some of the measurement techniques covered in this guide. These revisions will be included in future updates of this document.

The theory of SE of planar materials in this guide is highly simplified and is only intended to illustrate primary principles and to clarify the basic concept of each measurement technique. For a greater understanding of the SE regarding EM waves, the reader is advised to consult the many excellent mathematical treatments in books and papers available through the IEEE and other technical publishers.

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IEEE Guide for the Characterization of the Shielding Effectiveness of Planar Materials

1. Overview

1.1 Scope

This guide provides methods and procedures for determining the shielding effectiveness (SE) of planar materials. Such materials might comprise, but are not limited to, metals, coated plastics, fiber-filled polymers, and textiles. Guidance is provided to the user for the selection of the appropriate test method to determine the level of shielding provided in the intended application.

1.2 Background

The ideal EM shield is an infinitely conductive enclosure with no apertures or penetrations of any kind. Functional requirements and practicalities of design and construction prevent this ideal from being realized. Penetrations for power, signals, and ventilation, as well as access apertures for calibrations, controls, and adjustments, could be incorporated into an enclosure preventing it from being an ideal enclosure. An enclosure should include all the intended design features when evaluating it for its SE.

Depending on function and application, electronic equipment operates in an extremely wide range of EM environments in terms of both intensity and frequency. The environment can vary from that of the home to the battlefield. Because there is no “one size/type fits all” enclosure, the challenge facing equipment designers is that of choosing the most efficient and cost-effective shielding material for the enclosure intended for that particular application.

An essential parameter in this selection process is the SE of the material under the surrounding conditions of the application. It should be repeated that the final performance of the shielding enclosure will also depend on the different aspects of the enclosure design, including apertures, the closing of different parts, and the use of an appropriate gasket. Due to the high variety of applications, including the size and shape of the enclosures, the shielding material is normally characterized as a planar material, but under different field conditions. Depending on the frequency range, different measurement techniques may be used to cover the entire frequency range of interest. A table summarizing the different methods and their main characteristics is provided in [Annex A](#).

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6, 7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ASTM D4935-18, Standard Test Method for Measuring the Electromagnetic Shielding Effectiveness of Planar Materials, ASTM, 2018.⁸

IEEE Std 299™-2006, reaffirmed 2012, IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures.^{9,10}

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹¹

decibel (dB): Ten times the logarithm to base 10 of a ratio of two powers.

dBμA/m: Field strength of the magnetic field in decibels referenced to one microampere per meter (μA/m), 20 log(field strength/1 μA/m).

dBμV/m: Field strength of the electric field in decibels referenced to one microvolt per meter (μV/m), 20 log(field strength/1 μV/m).

dBm: Decibels referenced to one milliwatt (mW), 10 log(field strength/1 mW).

⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

⁸ASTM publications are available from the American Society for Testing and Materials (<https://www.astm.org/>).

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¹¹*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

dynamic range (DR): The range of amplitudes over which the receiving system operates linearly. For a measurement, the DR is the difference between the input level, which may be determined by the available transmit power or the upper limit of the received power, and the minimum discernible signal above the noise floor, normally with an amplitude of 3 dB (or more) above the noise floor.

electromagnetic compatibility (EMC): The ability of a device, equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

electromagnetic interference (EMI): Any conducted or radiated electromagnetic energy that interrupts, obstructs, or otherwise degrades or limits the effective performance of telecommunications or other electrical and electronic equipment.

far field: For shielding purposes, the far field is defined as the electric and magnetic field of an antenna at distances more than one-sixth ($\lambda/2\pi$) the wavelength of the carrier signal being used for communications. In this region, waves are dominated by planar wave mode transmission.

insertion loss (IL): The loss of signal power from one port of the device under test (DUT) to another port, resulting from the insertion of the DUT. It is also used synonymously with S21.

measurement uncertainty: The limits of error about a measured value between which the true value will lie with the confidence stated.

mode stirred chamber: An electromagnetic reverberation chamber (e.g., an electrically large non-anechoic shielded chamber) used to generate an average, uniformly homogeneous electromagnetic field that is achieved by changing the boundary conditions (e.g., by rotating an irregularly-shaped mode stirrer or tuner).

near field (NF): The electric and magnetic field of an antenna at distances less than one-sixth ($\lambda/2\pi$) the wavelength of the carrier signal being used for communications. In this region, waves are dominated by capacitive and magnetic coupling modes.

repeatability: The closeness of agreement among a number of consecutive measurements of the output for the same value of the input under the same operating conditions.

shielding effectiveness (SE): The ratio of the signal received (from a transmitter) without the shield to the signal received inside the shield; the insertion loss when the shield is placed between the transmitting antenna and the receiving antenna.

TEM cell: A measuring device that is designed to utilize the transverse electromagnetic (TEM) mode over the frequency range of interest. Common examples are the two-port TEM cell (also known as the Crawford cell) and the wideband TEM cell.

VIRC: Vibrating intrinsic reverberation chamber is a reverberation chamber without a mode stirrer, but with moving (vibrating) walls, so that the resonant patterns are disturbed. Is used as an alternative for the mode stirred chamber.

3.2 Acronyms and abbreviations

DR	dynamic range
EM	electromagnetic
EMC	electromagnetic compatibility
EMI	electromagnetic interference
GRL	gated-reflect-line
IL	insertion loss

LF	low frequency
LUF	lowest usable frequency
MUT	material under test
NF	near field
RC	reverberation chamber
SE	shielding effectiveness
TEM	transverse electromagnetic
TRL	thru-reflect-line
VIRC	vibrating intrinsic reverberation chamber
VNA	vector network analyzer

4. Factors affecting the shielding effectiveness (SE) of planar materials

This clause deals with some basic parameters affecting the SE of homogeneous conductive planar materials. A more detailed analysis dealing with the wave impedances is given in [Annex B](#). Specific adapted formulae for the conductivity σ of the material will be needed in the case of non-homogeneously conductive materials such as grids and meshes.

[Figure 1](#) illustrates an EM wave impinging on a planar material, the basic model starts from three effects which together determine the SE. This model is also called the Schellkunoff model.

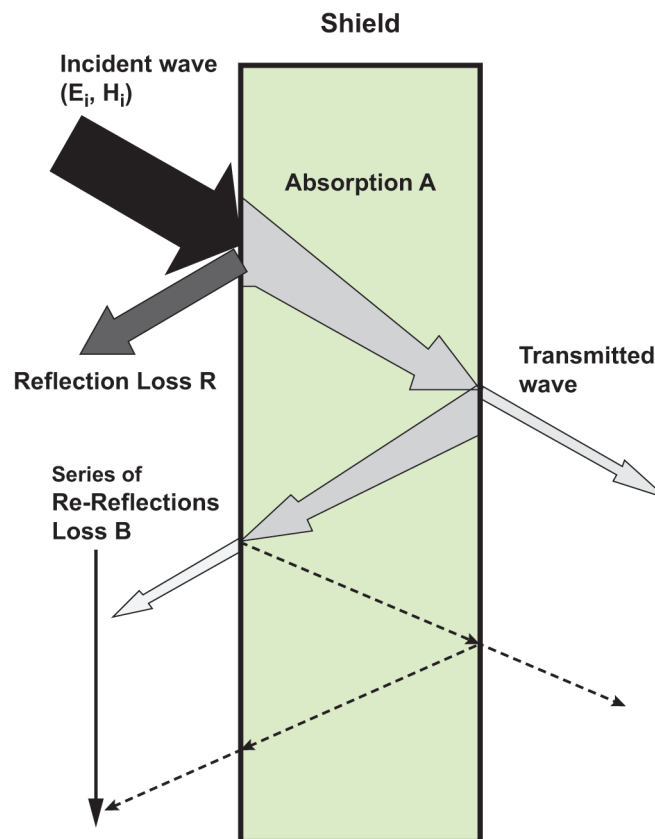


Figure 1—Wave interaction on the surface of a shielding material

The three basic effects are:

- Reflection R of the impinging wave by the shielding material
- Attenuation A of the transmitted wave in the material, due to the skin depth
- Re-reflection effect B , when the transmitted wave is leaving the shielding material, and consequently a number of reflections/transmissions occur at both surfaces, inside the material.

The reflection loss R is where part of the impinging wave is reflected at the surface of the planar material and a second time at the second surface of the material. The shielding achieved by the reflection can be expressed in decibels as:

$$R_{dB} = -20 \log \left(\left| (1 + \Gamma)(1 - \Gamma) \right| \right) \quad (1)$$

$$\Gamma = \left[\left(\frac{Z_{material}}{Z_{wave}} \right) - 1 \right] / \left[\left(\frac{Z_{material}}{Z_{wave}} \right) + 1 \right] \quad (2)$$

where

Γ is reflective coefficient

$$Z_{wave} = 120\pi \times K \quad (3)$$

K is a factor according to the near field (NF) (E or H) or far field, where:

- $K = 1$ for far field (plane wave)
- $K = \omega r / c$ for NF magnetic field SE
- $K = c / \omega r$ for NF electric field SE
- $\omega = 2\pi f$, where
 - f is frequency
 - c is the speed of light in free space
 - r is distance

The transition from NF to far field is defined by the source to a material distance of $d = \lambda / 2\pi$.

Concerning the material impedance $Z_{material}$, the impedance is given by

$$Z_{material} = \sqrt{\left(\frac{j\omega\mu}{j\omega\epsilon + \sigma} \right)} \quad (4)$$

For highly conductive materials, Equation (4) can be written as:

$$Z_{material} = \sqrt{\left(\frac{\omega\mu}{2\sigma} \right)} (1 + j) \quad (5)$$

where

μ is permeability
 σ is conductivity

An appropriate value or expression can be used for σ in case of non-homogeneous materials.

A is the attenuation of the impinging wave when passing through the planar material. For thin materials ($t \ll \delta$), the contribution of A is neglectable, expressed in decibels as:

$$A_{dB} = 8.686 \frac{t}{\delta} \quad (6)$$

where

t is thickness of the material
 δ is penetration depth

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} \quad (7)$$

An appropriate value or expression can be used for σ in case of non-homogeneous materials.

A correction factor B “re-reflection” needs to be applied if A is small, typically when the material is thin compared to the skin depth, which suffer from internal multiple reflections and re-transmissions. For thicker materials, the internal reflections are suppressed by the attenuation A.

$$B_{dB} = 20 \log \left(\left| 1 - \Gamma^2 e^{-\frac{2t}{\delta}} \right| \right) \quad (8)$$

The total SE value is given by:

$$SE_{dB} = R_{dB} + A_{dB} + B_{dB} \quad (9)$$

In 1938, Schelkunoff published a paper on the concept of using impedance to simulate shielding problems (“The impedance concept” [B27]).¹² Known as the *wave theory*, it applied to shielding problems of the transmission line model. Table 1 summarizes formulae for the estimation of SE under different conditions. For thin materials ($t < \delta$), the permeability (μ_r) has no influence on the SE; for thicker materials, the thickness, μ_r , and σ determine the SE of the material.

**Table 1—Schelkunoff’s formulae for the estimation of SE under different conditions
 (“The impedance concept” [B27])**

Field condition	Shielding (dB) $t > \delta$ (A + R)	Shielding (dB) $t < \delta$ (R + B)
Far field ($r > 1/2p$)	$8.69 \frac{t}{\delta} + 20 \log \left[\frac{1}{4} \left(\frac{\sigma}{\omega \epsilon_0 \mu_r} \right)^{\frac{1}{2}} \right]$	$20 \log \left[1 + \frac{Z_0}{2R_s} \right]$
Near electric dipole field ($r < 1/2p$)	$8.69 \frac{t}{\delta} + 20 \log \left[\frac{1}{4} \frac{c}{\omega \epsilon} \left(\frac{\sigma}{\omega \epsilon_0 \mu_r} \right)^{\frac{1}{2}} \right]$	$10 \log \left[1 + \left(\frac{c}{\omega \epsilon} \frac{Z_0}{2R_s} \right)^2 \right]$
Near magnetic dipole field ($r < 1/2p$)	$8.69 \frac{t}{\delta} + 20 \log \left[\frac{1}{4} \frac{\omega \epsilon}{c} \left(\frac{\sigma}{\omega \epsilon_0 \mu_r} \right)^{\frac{1}{2}} \right]$	$10 \log \left[1 + \left(\frac{\omega \epsilon}{c} \frac{Z_0}{2R_s} \right)^2 \right]$

R_s (DC square resistance of the material) = $1/(\sigma t)$

t = material thickness

Z_0 (plane wave impedances) = 120π (or 377Ω).

¹²The numbers in brackets correspond to those of the bibliography in Annex C.

In Catrysse, Vanhee, Pissort, and Celozzi [B4], the differences in low frequency (LF) magnetic field SE between the methods of NSA 94-106 [B25] and IEEE Std 299™-2006¹³ have been described from a practical point of view. Measurements show a difference in SE values, and concerning the NSA 94-106 method, the direct impact of the radius of the transmitting antenna has been demonstrated. The resulting SE values obtained by the IEEE Std 299-2006 are in good agreement with the theoretical wave model as defined by Schelkunoff (Table 1). SE values for the LF magnetic field condition, obtained by the NSA 94-106 document [B25] are in good agreement with a similar theoretical wave model, by using an adapted formula for the wave impedance, as described in a paper by Whitehouse [B34].

5. Standardized SE measurement techniques

5.1 ASTM D4935–18

5.1.1 General

ASTM D4935–18 describes the procedure and apparatus to measure directly and quantitatively the SE of planar materials illuminated by a far field, normally incident EM plane wave.

The test fixture adopted by ASTM D4935–18 is based on the apparatus developed at the National Bureau of Standards (NBS)/NIST and described by Wilson and Ma [B33]. It was mainly designed to overcome the measurement issues arising in case of poor electrical contacts between a material under test (MUT) with high-resistivity or insulated surfaces and the metallic conductors of the coaxial cell described in the standard ASTM-ES7-83 (withdrawn in 1988) [B1].

The ASTM D4935-18 standard was originally approved in 1989. It was withdrawn in 2005 and then reissued with minor changes. The current edition was published 1 May 2018.

5.1.2 Measuring principle

The method lies in the measurement of the insertion loss (IL) that results when introducing test samples in to a coaxial two-conductor transmission line holder, supporting transverse EM (TEM) propagation mode.

More specifically, the specimen holder of the standard, as sketched in Figure 2, consists of a two-port flanged and expanded coaxial cell with a constant 50 Ω characteristic impedance along its entire length and two center conductors terminating at the flange faces.

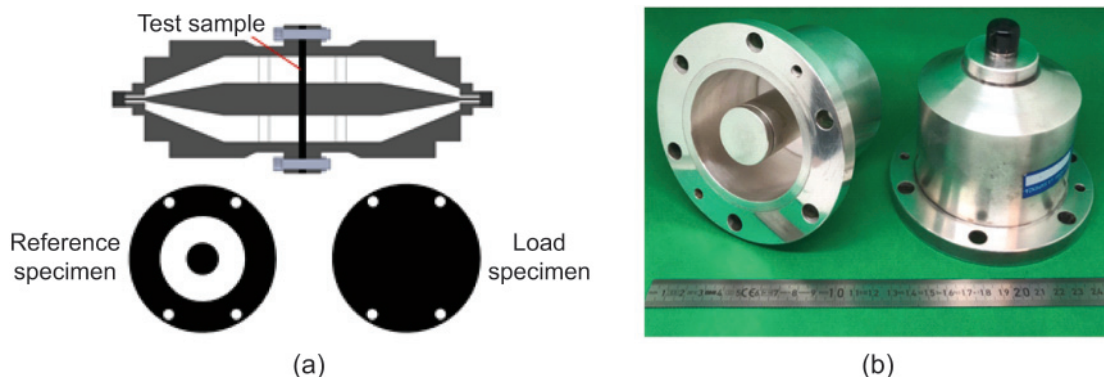


Figure 2—(a) Sketch of the typical longitudinal section of a flanged coaxial sample holder complying with ASTM D4935–18 together with load and reference specimens; (b) two halves of a flanged coaxial sample holder for SE measurements up to 1.5 GHz

¹³Information on references can be found in Clause 2.