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IEEE Standard Method for Measuring the Shielding Effectiveness of Enclosures and Boxes Having all Dimensions between 0.1 m and 2 m

IEEE Electromagnetic Compatibility Society

Sponsored by the
Standards Development Committee

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IEEE Std 299.1™-2013

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Approved 31 October 2013

IEEE-SA Standards Board

Abstract: This standard provides uniform measurement procedures for determining the shielding effectiveness of electromagnetic (EM) shielding for a variety of enclosures and boxes having all dimensions between 0.1 m and 2 m in the radio frequency range not addressed by IEEE Std 299™-2006. This standard is divided into two parts: Part I – 0.75 m to 2 m and Part II – physically small (< 0.75 m) but electrically large enclosures. In addition to a number of annexes aiding the measurement of shielding effectiveness of these enclosures, Annex I addresses physically small and electrically small enclosures, and Annex J addresses electrically small enclosures in reverberation chambers. Problems occurring in the testing of small enclosures having linear dimension less than 2 m are very different from determining the shielding effectiveness of large rooms and broad depending on the actual size of the enclosure itself. A number of other annexes are included that address rationale, mathematical formulas, selection of measurement techniques, preliminary measurement and repairs, wall-mounted monopoles, impedance mismatch correction, and using isolated monopoles in outer reverberation chambers.

Keywords: electrically large, electrically small, electromagnetic shielding, IEEE 299.1™, physically large, physically small, reverberation chamber, shielded enclosure, shielding effectiveness

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PDF: ISBN 978-0-7381-8895-9 STD98524
Print: ISBN 978-0-7381-8896-6 STDPD98524

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Introduction

This introduction is not part of IEEE Std 299.1™-2013, IEEE Standard Method for Measuring the Shielding Effectiveness of Enclosures and Boxes Having all Dimensions between 0.1 m and 2 m.

Enclosures and boxes constructed from various metals and other materials such as plastics coated with various metallic coatings are used to provide shielding against radiated emissions in various frequency ranges. Enclosures and boxes shall contain apertures to allow objects to pass through the shield to reach equipment inside the shield. A particular threat is represented by intended apertures whose radiation cannot be mitigated by electromagnetic gasketing. In particular, heat dissipation requirements fix a lower bound on aperture size. This is the reason why equipment-level enclosures typically offer a shielding effectiveness (SE) ranging from low to medium values.

The measurement of the SE of an enclosure is standardized in IEEE Std 299™-2006, IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures. While in the case of a large enclosure, the method does not show any particular problems, in the case of a small enclosure, some problems arise, especially in the definition of SE. IEEE Std 299-2006 does not address tile measurement of the shielding effectiveness of enclosures having minimum linear dimension smaller than 2 m. IEEE Std 299-2006 provides uniform measurement procedures for determining the effectiveness of electromagnetic (EM) shielding enclosures at frequencies from 9 kHz to 18 GHz (extendable down to 50 Hz and up to 100 GHz).

More precisely, a distinction is necessary between physically small but electrically large enclosures, and those that are both physically and electrically small. The former successfully allows a reverberation chamber (RC) method to be applied for SE evaluation by means of the frequency stirring technique in [B5][a] and [B23]. For the latter case, the traditional SE definition is hard to apply because of the undermoded condition, the strong dependence of the internal field on probe positioning and orientation, and the dependence on the incoming field polarization. For these reasons, an IEEE 299.1 Working Group was formed and engaged in effectively standardizing the case of small enclosures.

IEEE Std 299.1-2013, IEEE Standard Method for Measuring the Shielding Effectiveness of Enclosures and Boxes Having all Dimensions between 0.1 m and 2 m, is an extension of IEEE Std 299-2006. The purpose of IEEE Std 299.1-2013 is to provide test procedures for the measurement of the shielding effectiveness of enclosures whose maximum linear dimension is less than 2 m and whose minimum linear dimension is greater than 0.1 m. IEEE Std 299.1-2013 focuses on the test procedures for measuring the shielding effectiveness of small enclosures and boxes having linear dimensions between 0.1 m and 2 m at frequencies from 9 kHz to 18 GHz. This is a subclass of the enclosure not covered by the existing IEEE Std 299-2006; in fact, problems occurring in the testing of small enclosures, having linear dimension less than 2 m, are very different and broad depending of the actual size of the enclosure itself. Different sizes of small enclosures will be the scope of further standards on this subject.

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[a] The numbers in brackets correspond to those of the bibliography in Annex L.

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1. Overview

IEEE Std 299.1™-2013, IEEE Standard Method for Measuring the Shielding Effectiveness of Enclosures and Boxes Having all Dimensions between 0.1 m and 2 m, is an extension of IEEE Std 299™-2006, IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures.[1] IEEE Std 299.1-2013 focuses on the test procedures for measuring the shielding effectiveness (SE) of small enclosures and boxes having linear dimensions between 0.1 m and 2 m. This is a subclass of the enclosure not covered by the existing IEEE Std 299-2006; in fact, problems occurring in the testing of small enclosures, having linear dimension less than 2 m, are very different and broad depending on the actual size of the enclosure itself. New definitions and test methods described in this standard can be applied to determine the shielding effectiveness for enclosures with apertures used in a variety of applications including power supplies, variable speed drives, and electronic equipment housings. A number of annexes are included that address rationale, mathematical formulas, selection of measurement techniques, preliminary measurement and repairs, wall-mounted monopoles, impedance mismatch correction, and using isolated monopoles in reverberation chambers. Other international standards, such as IEC 61000-5-7 on the protection provided by shielded enclosures, and IEC 61587-3 (Ed. 2) on the shielding performance of cabinets, racks, and subracks, are relevant to this standard, and those engaged in testing the shielding effectiveness of enclosures may want to refer to them.

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[1] Information on normative references can be found in Clause 2.

1.1 Scope

This standard provides uniform measurement procedures for determining the effectiveness of electromagnetic (EM) shielding for a variety of physically small and large and electrically small and large enclosures within specified frequency ranges.

1.1.1 Document organization

To address each type of enclosure in one standard, Clause 7, Test procedures, is divided into two parts as described below. A number of annexes are included in this standard to provide supporting discussion on topics relevant to the subject of this standard. A brief description of the annexes is presented below.

Annex A includes considerations to constrain the effort and associated costs involved in the measurement (for 0.75 m to 2 m enclosures) method aimed to combine technical validity with a minimum of testing. Annex B includes the description of mathematical formulas and specific definitions for measures of enclosure performance for each associated measurement procedure. Annex C includes a miscellaneous supporting information for the 0.75 m to 2 m enclosures. Annex D describes the guidelines for the selection of measurement techniques for the 0.75 m to 2 m enclosures. Annex E contains recommendations for procedures to perform a cursory check (not required by the standard) on the shield for efficiency reasons in order to establish if the shield requires minor, and possibly major, repairs before the SE measurements are made. Annex F discusses the rational of using a wall-mounted monopole and shows how the power in an enclosure can be measured either in the center of the enclosure or at the wall of an enclosure. Annex G discusses in detail the rational for the mismatch correction discussed in 7.2.2. Annex H describes the use of isolated monopoles in outer reverberation chamber. Annex I addresses physically small and electrically small enclosures. Annex J addresses the testing of electrically small enclosures in reverberation chambers. Annex K addresses the utilization of absorbing (dissipative) materials in equipment enclosures for the measurement of shielding properties. Annex L includes the bibliographical entries that are cited in the text for this standard.

1.1.1.1 Clause 7, Test procedures, Part I – 0.75 m to 2 m enclosures

Part I of Clause 7 of this standard provides uniform measurement procedures for determining the effectiveness of EM shielding enclosures at frequencies from 9 kHz to 18 GHz (extendable up to 100 GHz). The owner of the shielding enclosure shall provide the frequencies at which the shield will be tested, and the shielding effectiveness limits for pass/fail criteria. Part I of Clause 7 of this standard suggests a range of test frequencies that would provide very high confidence in the effectiveness of the shield. No attempt to define the results of testing enclosures is made in Part I of Clause 7 of this standard.

1.1.1.2 Clause 7, Test procedures, Part II – Physically small (< 0.75 m) and electrically large enclosures

Part II of Clause 7 of this standard addresses physically small, but electrically large enclosures. “Physically small” is defined as an enclosure less than 0.75 m on a side, and “electrically large” refers to an enclosure that supports several modes at the lowest frequency of interest, as discussed in 7.2. The procedure discussed in this part of the standard utilizes the reverberation chamber frequency-stirring technique presented in [B14][2] and [B15]. The owner of the shielding enclosure shall provide the frequencies at which the shield will be tested, and the shielding effectiveness limits for pass/fail. However, Part II of Clause 7 of this standard suggests a range of test frequencies that would provide very high confidence in the effectiveness of the shield. Part II of Clause 7 of this standard does not attempt to define what the SE results of enclosure testing should be.

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[2] The numbers in brackets correspond to those of the bibliography in Annex L

1.1.1.3 Annex I (informative) – Measuring the shielding effectiveness of physically small and electrically small enclosures using magnetic field measurements (≤ 300 MHz)

This annex addresses the electromagnetic shielding of small enclosures, over the frequency range where they are electrically small. For the purposes of this standard, the physically small enclosures have dimensions that are in the range of 0.1 m to 0.75 m. Being electrically small means that the upper frequency for credible measurements shall be such that the wavelength is large compared to the largest dimension of the enclosure. Alternatively, the largest dimension of the enclosure shall be small compared to the wavelength. This requirement is satisfied if the following conditions are met by Equation (1) as:

$$\ell < \frac{\lambda}{10} \tag{1}$$

Where ℓ is the largest dimension of the enclosure and λ is the shortest wavelength that can be used for valid measurements. This is considerably smaller than the wavelength of the first resonance. These criteria can be converted to upper bound frequencies, since using Equation (2) as:

$$f = \frac{c}{\lambda} \ or\ \lambda = c/f \tag{2}$$

Where c is the speed of light (approximately 3×10^8 m/s in air), this condition is equivalent to the expression given by Equation (3) as:

$$f < \frac{c}{10\ell} \tag{3}$$

This also means that the upper frequency, f, shall be less than 300 MHz for an enclosure whose longest interior dimension is equal to 0.1 m and less than 40 MHz for an enclosure whose longest dimension is shorter than 0.75 m. Note that these upper bound frequencies are considerably less than the half wavelength cavity resonance frequencies (1.5 GHz and 200 MHz respectively). Additional constraints on the upper frequency limit are imposed by the size and design of the test fixture and sensors.

Annex I of this standard only describes how to measure the magnetic field shielding effectiveness for the principal component, namely the component that is normal to the current flow. The non-principal components are assumed to be smaller. If other orientations are desired, the enclosure may be reoriented in the test fixture. Additional information relating to Annex I can be found in [B13] and [B4].

Although many standards seek to measure the magnetic and electric field shielding, this standard only measures the magnetic field shielding effectiveness. This is sometimes called the surface magnetic field attenuation. The assumption is made that the electrically small enclosure is made of conductive material having a surface resistance of less than a few ohms per square and a thickness of several skin depths. Under these conditions, an electric field cannot exist because it is shorted out by the enclosure walls.

1.1.1.4 Annex J (informative) – Electrically small enclosures in reverberation chambers

This annex addresses the measurement of shielding effectiveness of small enclosures. More precisely, a distinction is necessary between physically small but electrically large enclosures, and those that are both physically and electrically small. The former successfully allows a reverberation chamber (RC) method to be applied for SE evaluation by means of the frequency stirring technique in [B5] and [B9]. For the latter case, the traditional SE definition is hard to apply because of the undermoded condition, the strong dependence of the internal field on probe positioning and orientation, and the dependence on the incoming field polarization. Alternative SE definitions are also therefore under investigation for such enclosures [B23]. The aim of Annex J is to begin describing this complex issue. In particular, the field coupling in a typical equipment-level enclosure is evaluated when it is placed inside an RC.

1.2 Purpose

The purpose of this standard is to provide test procedures for the measurement of the shielding effectiveness of enclosures whose maximum linear dimension is less than 2 m and whose minimum linear dimension is greater than 0.1 m.

1.2.1 General document organization

1.2.1.1 Clause 7, Test procedures, Part I – 0.75 m to 2 m enclosures

The purpose of Part I of Clause 7 of this standard is as follows: a) To provide a standard procedure for the measurement of the effectiveness of shielded enclosures, in a broad range of radio frequencies, including a minimum set of recommended frequencies; b) To provide identical procedures applicable to frequencies other than the standard set; and c) To provide an optional measurement technique to detect the nonlinear behavior of high permeability ferromagnetic enclosures (see Annex C).

1.2.1.2 Clause 7, Test procedures, Part II – Physically small (< 0.75 m) and electrically large enclosures

The purpose of Part II of Clause 7 of this standard is as follows: a) to provide a standard procedure for the measurement of the effectiveness of shielded enclosures with all dimensions less than 0.75 m on a side for a minimum frequency range and higher. (The minimum frequency is defined as the frequency where several modes can be supported in the enclosure.); b) To provide identical procedures applicable for a large frequency range.

1.2.1.3 Annex I (informative) – Measuring the shielding effectiveness of physically small and electrically small enclosures using magnetic field measurements (≤ 300 MHz)

The purpose of Annex I is to describe how to measure the shielding effectiveness of physically small and electrically small enclosures over the frequency range where they are electrically small. Annex I describes how to measure the magnetic field shielding effectiveness for the principal component, namely the component that is normal to the current flow. The non-principal components are assumed to be smaller. If other orientations are desired, the enclosure may be reoriented in the test fixture.

1.2.1.4 Annex J (informative) – Electrically small enclosures in reverberation chambers

The purpose of Annex J is to effectively standardize the measurement of shielding effectiveness of small enclosures. A distinction is necessary between physically small but electrically large enclosures, and those that are both physically and electrically small. The former can be successfully tested for SE in an RC by means of the frequency stirring technique described in [B5] and [B9]. For the latter case, the traditional SE definition is hard to apply because of the undermoded condition, the strong dependence of the internal field on probe positioning and orientation, and the dependence on the incoming field polarization.

1.3 Application of test methods and use of this document

The measurement procedures provided in this standard depend on the physical and electrical dimensions of the enclosure under test. For Clause 7, Test procedures, Part I – 0.75 m to 2 m enclosures, the procedures apply to any enclosure having a smallest linear dimension between 0.75 m and 2 m. In addition, the enclosure shall be such that a person can enter and move an antenna around appropriately. For Clause 7, Test procedures, Part II – Physically small (< 0.75 m) and electrically large enclosures, the procedures apply to any enclosure having a largest linear dimension below 0.75 m and for a minimum frequency where several modes are supported in the enclosure. For Annex I, electromagnetic shielding of small enclosures is determined over the frequency range where the enclosure is electrically small. For the purposes of this standard, the small enclosures have dimensions that are in the range of 0.1 m to 0.75 m. Being electrically small means that the upper frequency for credible measurements shall be such that the wavelength is large compared to the largest dimension of the enclosure. Alternatively, the largest dimension of the enclosure shall be small compared to the wavelength. The upper frequency, f, shall be less than 300 MHz for an enclosure whose longest interior dimension is shorter than 0.1 m and less than 40 MHz for an enclosure whose longest dimension is shorter than 0.75 m. Note that these upper bound frequencies are considerably less than the half wavelength cavity resonance frequencies (1.5 GHz and 200 MHz respectively). Additional constraints on the upper frequency limit are imposed by the size and design of the test fixture and sensors. For Annex J, the field coupling in a typical equipment-level enclosure is evaluated when it is placed inside an RC.

This standard contains twelve annexes. Not all of the annexes provided here are for use with every part of this standard. The following describes the use of the annexes with the relevant part of this standard.

a) Clause 7, Test procedures, Part I – 0.75 m to 2 m enclosures.
    1) Annex A (informative) – Rationale (for Part I – 0.75 m to 2 m enclosures)
    2) Annex B (informative) – Mathematical formulas (for Part I – 0.75 m to 2 m enclosures)
    3) Annex C (informative) – Miscellaneous supporting information (for Part I – 0.75 m to 2 m enclosures)
    4) Annex D (informative) – Guidelines for the selection of measurement techniques (for Part I – 0.75 m to 2 m enclosures)
    5) Annex E (informative) – Preliminary measurements and repairs (for Part I – 0.75 m to 2 m enclosures)
b) Clause 7, Test procedures, Part II – Physically small (< 0.75 m) and electrically large enclosures.
    6) Annex F (informative) – Rationale for wall-mounted monopoles
    7) Annex G (informative) – Impedance mismatch correction
    8) Annex H (informative) – Using isolated monopoles in outer reverberation chamber
    9) Annex I and Annex J are provided to introduce the user to methods under further investigation.
c) Annex I (informative) – Measuring the shielding effectiveness of physically small and electrically small enclosures using magnetic field measurements (≤ 300 MHz).
d) Annex J (informative) – Electrically small enclosures in reverberation chambers.
e) Annex K is provided to help users understand proper utilization of dissipative materials in enclosures when making shielding effectiveness measurements.
f) Annex K (informative) – Utilization of absorbing (dissipative) materials in equipment enclosures for the measurement of its shielding properties.
g) Annex L is provided as the bibliography for this standard.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they shall 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. Another set of documents is listed in Annex L as references of engineering methodologies.

IEC 61000-4-21, Electromagnetic compatibility (EMC) — Part 4–21: Testing and measurement techniques – Reverberation chamber test methods. International Electrotechnical Commission (IEC), Geneva, Switzerland, (2011).[3]

IEC 61000-5-7, Electromagnetic compatibility (EMC) — Part 5–7: Installation and mitigation guidelines - Degrees of protection provided by enclosures against electromagnetic disturbances (EM code), (2001).

IEC 61587-3 Ed. 2, Mechanical structures for electronic equipment — Tests for IEC 60917 and IEC 60297 – Part 3: Electromagnetic shielding performance tests for cabinets and subracks, (2013).

IEEE Std C95.1™-2005, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz.[4, 5]

IEEE Std 299™-2006, IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures.

3. Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be consulted for terms not defined in this clause.[6]

3.1 General terminology

shall: The use of this verb in a direction means that the following actions or procedures are mandatory to implement the standard.

should: The use of this verb in a direction means that the following actions or procedures are recommended to implement the standard.

3.2 Technical terminology

accessible test location: A test location that can be reached by a test antenna or probe without modifying a parent structure.

dynamic range (DR): The range of amplitudes over which the receive system operates linearly. For a measurement, the DR is the difference between the reference level and the minimum discernable signal

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above the noise floor. The minimum discernable signal is defined as one with amplitude of 3 dB or more above the test system noise floor.

NOTE— This is what should be verified during the DR validation step of the SE procedures defined in 4.4 and 4.5 of this standard, and represents the maximum SE measurable at that frequency with that particular equipment and settings.[7]

electrically large: An enclosure that supports several modes at the lowest frequency of interest.

frequency stirring: A process applied to a shielded enclosure to facilitate the analysis in the high frequency range where a high mode density occurs.

local source: An emitter located close enough to a shielding enclosure for its electromagnetic energy to illuminate only a localized portion of a shielding face. The effect is assessed by choosing the poorest performance in the set of measured locations.

mode: A spatial field distribution inside an enclosure for a given enclosure size, shape, and for a given frequency. For a given enclosure size, there will be a finite allowable number of modes for a given frequency for the approach discussed in this standard to be valid.

mode stirring: The use of a mechanical stirrer(s) to vary the mode fields and excitations in order to generate a statistically uniform field in a reverberation chamber.

owner (shielded enclosure user or owner): The individual, corporation, or organization that intends to use the shield and that is the ultimate source of the shielding requirement.

parent structure: A permanent enclosure or outside housing that contains the shielding enclosure.

physically small: An enclosure less than 0.75 m on a side.

reverberation chamber: A metal enclosure large enough to support a large number of modes used to develop a statistical electromagnetic test environment. The statistical environment is generated with either mechanical and/or frequency stirring (Adapted from IEC 61000-4-21).

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.

shielding enclosure: A structure that protects its interior from the effect of an exterior electric or magnetic field, or, conversely, protects the surrounding environment from the effect of an interior electric or magnetic field. A high-performance shielding enclosure is generally capable of reducing the effects of both electric and magnetic field strengths by one to seven orders of magnitude depending upon frequency. An enclosure is normally constructed of metal with provisions for continuous electrical contact between adjoining panels, including doors, vents, and other required openings.

testing organization: The organization that actually performs the tests and records the data.

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[7] Notes in standards are informative.

4. Preparing for shielding effectiveness measurements – preliminary procedures

There are a number of preparations that shall be made prior to measuring the shielding effectiveness of any shielded enclosure. The preparations described here apply to various parts of this standard. Detailed procedures required for the measurement of shielding effectiveness are discussed in Clause 7.

4.1 Background

Reading and following the preparations listed here in this clause prior to conducting shielding effectiveness measurements will help to ensure that correct measurement procedures are followed and that the shielding effectiveness data is accurate and repeatable. Examples of required preparations include reference measurement of the dynamic range of the measurement equipment. Verification of the dynamic range during the tests may be needed. However, preparations such as checking the initial performance of the shield prior to the collection of measurement data are not required by this standard. Annex E of this standard discusses additional preparations that may be carried out prior to measuring shielding effectiveness.

4.2 Test plan

A test plan shall be prepared. The plan shall be approved by the owner or owner's representative prior to the start of tests. Tests shall be performed in accordance with the approved test plan. The test plan shall include, but not be limited to, actual test frequencies, test result pass/fail requirements, test locations, and a proposed equipment list. In addition, requirements for maintenance of a test log and an accepted procedure for making changes to the test plan that may arise during testing should be included.

4.3 Calibration

Any piece of EMC measurement equipment (e.g., spectrum analyzer, antenna, etc.) that affects the numerical value of the shielding effectiveness shall be in calibration before any measurements are conducted. Equipment calibration certificates shall accompany the equipment, including calibration date and company performing the calibration, all traceable to a national calibration standard. No equipment affecting the numerical value of measured shielding effectiveness that is outside of the calibration date cycle shall be used to conduct shielding effectiveness measurements.

4.4 Reference level

As a part of the measurement process, a reference level shall be determined as described in the measurement procedures. The determination of reference level shall be made to assure that changes in the test setup do not affect the reference level resulting from changes in the test setup. The reference level shall also be re-measured at the conclusion of each test procedure when measurement frequency is often changed. If the measurement reference level verification varies from the initial reference level by more than ± 3 dB, then the test procedure shall be repeated, including reference level measurements.

4.5 Dynamic range (DR)

Each unique equipment configuration used to measure SE shall be demonstrated to have adequate dynamic range (DR). Determination of the DR shall consist of excitation of the receiving equipment with the associated transmitting equipment, and demonstration that the equipment remains calibrated (linear) for all levels of received and transmitted signals that are actually experienced during the test. This demonstration shall be accomplished by varying the receiver input with a calibrated attenuator external to the receiver and observing an equal change, in decibels, in the receive system. Alternatively, the internal input attenuator of the instrument can be used. In this case, linear operation is present if no change in signal amplitude is observed when changing the input attenuator setting. This test shall be done at least once for each test or each band of test frequency if an individual test contains more than one test band.

The DR shall be at least 6 dB greater than the SE to be measured. DR can most efficiently be determined during the reference measurement. Effects of surrounding structure (walls, buildings, etc.) shall be minimized.

4.6 Personnel in shielded enclosure (tester and witness)

It is not desirable to have personnel within the shielded room while testing the enclosure. If required, a maximum of two (2) people are allowed within the shielded room. This is intended to allow a tester and a witness.

4.7 Preliminary shield check procedures

Please see Annex E for a description of these procedures.

4.8 Reverberation qualification (7.2 and Annex J only)

The technique discussed in this standard requires the use of a reverberation chamber. There are processes in place for determining if a reverberation chamber meets a given performance guideline. This process is spelled out in IEC 61000-4-21. Thus, any reverberation chamber used in this test shall meet the minimum performance requirements given in IEC 61000-4-21. This requirement ensures that the outer reverberation chamber meets a field uniformity constraint in order to attain independent samples for the averaging procedure used in obtaining the SE as defined in Equation (8).

In this procedure, the outer reverberation chamber should meet performance requirements and/or criteria as defined in IEC 61000-4-21. This requirement ensures that the outer reverberation chamber meets a field uniformity constraint in order to attain independent samples for the averaging procedure used in obtaining the SE as defined in Equation (8).

4.9 Pass/fail requirements

The minimum acceptable pass/fail requirements for shielded effectiveness testing shall be defined by the owner.

4.10 Usable frequency ranges and limits (7.2 only)

Test frequencies shall be chosen by the owner. However, there is a minimum frequency limit in this measurement procedure for 7.2 of this standard. In order for the frequency stirring approach to be valid, the enclosure shall be able to support at least 60 modes for a given enclosure size and frequency. Thus, the minimum frequency that this procedure can be used for is a given enclosure size is given by Equation (4):

$$f_{\mathbf{min}} = c\left(\frac{90}{4\pi}\frac{1}{V}\right)^{1/3} \tag{4}$$

where V is the volume of the small enclosure in cubic m, and c the speed of light in m/s in air. Figure 1 plots this function for volumes as large as 1 m^3.

While there is a minimum frequency requirement in this measurement procedure, there is no upper frequency requirement. However, the upper frequency may be governed by the test equipment used such as the VNA, cables, and antennas.

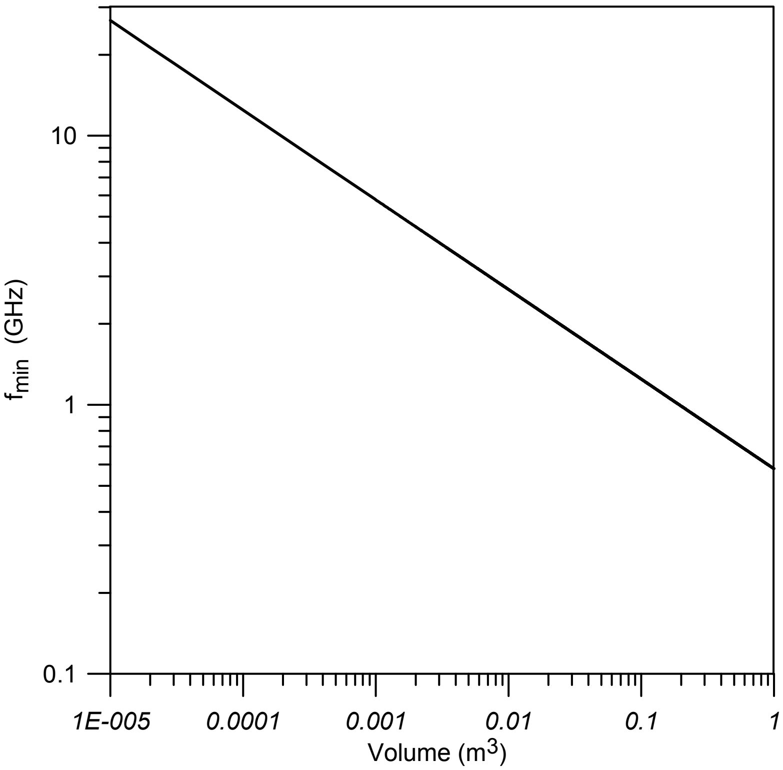

Figure 1—Minimum frequency versus enclosure volume

5. Measurement instrumentation

Various types of generation, matching, and measurement equipment used in electromagnetic compatibility work are required to perform measurements of shielding effectiveness. Table 1, Table 2, Table 3, Table 4, and Table 5 describe this equipment for each part of the test procedure.

Table 1—Measurement instrumentation for shielding effectiveness measurements for Part I: Low-frequency small-loop method

Test Procedure Part of This Standard	Type of Equipment	Description of Equipment
Part I – 0.75 m to 2 m enclosures: Low-frequency small-loop method	Electromagnetically shielded loop antenna, quantity of two	0.3 m loop antenna that is electromagnetically shielded against electric fields used to generate the source of magnetic field; the other antenna is used as the receiving antenna.
	Audio frequency generator	Frequency generator that provides the signal in the audio frequency range for the audio frequency amplifier.
	Audio frequency amplifier	Amplifier that provides the current to the antenna.
	Impedance matching device	Device that matches the impedance between the amplifier and antenna.
	Field-strength meter	Device that measures the strength of the field generated by the antenna.
	Spectrum analyzer	Device that can be used to measure the field strength when fed from a calibrated antenna.

Table 2—Measurement instrumentation for shielding effectiveness measurements for Part I: High-frequency (non-resonant) method

Test Procedure Part of This Standard	Type of Equipment	Description of Equipment
Part I – 0.75 m to 2 m enclosures: High-frequency non-resonant method	Antennas	Dipoles, biconical antennas, horns, yagis, log periodic, or other linear antenna types that can generate a continuous wave (CW) field.
	Field-strength meter	Device that measures the strength of the field generated by the antenna.
	Spectrum analyzer	Device that can be used to measure the field strength when fed from a calibrated antenna.

Table 3—Measurement instrumentation for shielding effectiveness measurements for Part II

Test Procedure Part of This Standard	Type of Equipment	Description of Equipment
Part II – Physically small and electrically large enclosures	Antennas	Monopoles, dipoles, horn antennas, or other linear antenna types that can generate a CW field and can fit properly the small enclosure.
	Coaxial cables	Two conductor (center conductor, shield system), concentric, constant-impedance transmission line; doubly-shielded coaxial cables should be used.
	Vector network analyzer	Device that measures both amplitude and phase properties of electrical networks.

Table 4—Measurement instrumentation for shielding effectiveness measurements for Annex I

Test Procedure Part of This Standard	Type of Equipment	Description of Equipment
Annex I – Physically small and electrically small enclosures	Strip-line test fixture	A test fixture consisting of two parallel plates consisting of a strip line circuit.
	Radio frequency (RF) power amplifier	Power amplification device that amplifies a (radio) high-frequency signal to a higher power level.
	Vector network analyzer	Device that measures both amplitude and phase properties of electrical networks.
	RF signal source	A signal generator that generates a radio-frequency signal of varying amplitude and frequency.
	RF power attenuators	Attenuators designed to absorb radio-frequency power at specific levels.
	Loop sensors	A loop used alone to produce an alternating current (AC) magnetic field to test Equipment Under Test (EUT) for susceptibility (immunity) to magnetic fields in a low frequency range typically from 30 Hz to 100 kHz.
	Surface probes	Small inductively coupled sensors designed to measure the RF current flowing in a particular direction on a conducting surface.

Table 5—Measurement instrumentation for shielding effectiveness measurements for Annex J

Test Procedure Part of This Standard	Type of Equipment	Description of Equipment
Annex J – Electrically small enclosures in reverberation chambers	Antennas	Electric monopole.
	RF power amplifier	Power amplification device that amplifies a (radio) high-frequency signal to a higher power level.
	Vector network analyzer	Device that measures both amplitude and phase properties of electrical networks.
	Coaxial cables	Two conductor (center conductor, shield system), concentric, constant-impedance transmission line; doubly-shielded coaxial cables should be used.

6. Measurement uncertainty

Measurement uncertainty is a parameter that can be associated with the result of a measurement of shielding effectiveness. It characterizes the dispersion of values that could reasonably be attributed to the measurements. There are many aspects of SE where measurement uncertainty can be estimated to gain the overall expanded measurement uncertainty of the SE process contained in this standard. These include the uncertainties caused by the measurement instrumentation chain itself, the positioning of the transmit and receive antennas, the radio frequency (RF) loading of the room, and its effect on the room Q value, caused by the test personnel in the room, etc. Work is proceeding in addressing these uncertainty components. However, for the present and until this work is concluded, uncertainty is not required in the measurement of SE. It is recommended that a measurement uncertainty analysis be performed on each set of measurements and discussed in the final report. Clause 1 and Clause 2 list several references that can be used.

7. Test procedures

The test procedures for defining and determining the shielding effectiveness of various sizes of shielded enclosures with dimensions between 0.1 m and 2 m are provided and discussed below.

7.1 Part I – 0.75 m to 2 m enclosures

7.1.1 Background

This section contains the detailed procedures for the SE measurements for enclosures with dimensions 0.75 m to 2 m. This part of the standard defines a test procedure but does not define the frequencies at which the measurements should be made. This standard also does not define the minimum SE that constitutes a pass/fail criterion. The owner shall define these frequencies and all pass/fail requirements.

However, as a guide for owners, this standard recommends frequencies that can be selected for testing their shield. Successful tests conducted at these frequencies should provide very high confidence that a shield system provides the specified SE at all the frequencies covered by this standard.

WARNING

For all measurements undertaken as a part of this standard, care shall be taken to protect personnel from potentially hazardous RF field levels (IEEE Std C95.1-2005). This standard also suggests that authorization for transmit operation be obtained from the appropriate regulatory agency prior to activation of any transmitter. See C.2. Care shall also be taken to avoid interference with other electronic equipment operating in the vicinity.

7.1.2 Recommended measurement frequencies

Test frequencies shall be chosen by the owner. Recommended test frequencies are defined in Table 6. The frequency range from 20 MHz to 300 MHz is not included in Table 6, because this is the frequency range around resonance.

Table 6—Standard measurement frequencies

Frequency	Antenna Type	Procedure in this Standard
Low Range[8]		
9 kHz to 16 MHz	Small loop	7.1.5
16 MHz to 20 MHz	Small loop	7.1.5
High Range[9]		
0.3 GHz to 0.6 GHz	Dipole	7.1.7
0.6 GHz to 1.0 GHz	Dipole	7.1.7
1.0 GHz to 2.0 GHz	Horn	7.1.7
2.0 GHz to 4.0 GHz	Horn	7.1.7
4.0 GHz to 8.0 GHz	Horn	7.1.7
8.0 GHz to 18 GHz	Horn	7.1.7

The frequencies may be extended to higher ranges. Table 7 contains recommended frequencies in the extended ranges. The frequency ranges in Table 7 were based on IEEE Std 299-2006 where measurement ranges are given. Not all frequency ranges are covered in IEEE Std 299-2006 or in Table 7 of this standard. Further research is needed to address frequency ranges not covered in Table 7.

Table 7—Recommended extended range measurement frequencies

Frequency Range	Antenna Type	Procedure in this Standard
35 GHz to 45 GHz	Horn	7.1.7
90 GHZ to 100 GHz	Horn	7.1.7

7.1.3 Shielding effectiveness calculation

Data obtained by the measurement procedures of the following sections are converted to shielding effectiveness by mathematical relationships defined in Table 8 and Annex B. The magnitudes of the

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[8] Actual test frequencies shall be according to the approved test plan.

[9] A full size dipole may not fit in the shield under test.

quantities E_1, E_2, H_1, and H_2 are the field values measured using the antennas placed in the prescribed configuration.

Table 8—Mathematical shielded relationships[10]

Frequency range	Measured quantities	Units	Shielding effectiveness (dB)
Linear units			
9 kHz to 20 MHz (extendable down to 50 Hz)	$\lvert H_1\rvert, \lvert H_2\rvert$ $\lvert V_1\rvert, \lvert V_2\rvert$	µA/m, µV	$SE_H = 20 \log_{10} \frac{\lvert H_1\rvert}{\lvert H_2\rvert}$ $SE_V = 20 \log_{10} \frac{\lvert V_1\rvert}{\lvert V_2\rvert}$
300 MHz to 1.7 GHz, and 1.7 GHz to 18 GHz (extendable up to 100 GHz)	P_1, P_2	watts	$SE_P = 10 \log_{10} \frac{\lvert P_1\rvert}{\lvert P_2\rvert}$
Logarithmic units			
All frequencies (as listed above)	All, in dB related values	dB	$SE = \lvert E_1\rvert \text{ (dB)} - \lvert E_2\rvert \text{ (dB)}$ $SE = \lvert H_1\rvert \text{ (dB)} - \lvert H_2\rvert \text{ (dB)}$ $SE = \lvert V_1\rvert \text{ (dB)} - \lvert V_2\rvert \text{ (dB)}$ $SE = \lvert P_1\rvert \text{ (dB)} - \lvert P_2\rvert \text{ (dB)}$

7.1.4 Preparation procedures

Before detailed measurements are undertaken, the equipment shall be calibrated in accordance with 4.3, and reference levels and dynamic range shall be determined in accordance with 4.4 and 4.5, respectively.

7.1.5 Small-loop method – low-frequency measurements: 9 kHz to 20 MHz

Standard low-frequency measurements utilize a small electrostatically shielded loop that, because of its size, enables evaluation of the performance of the enclosure when exposed to magnetic sources near the enclosure walls.

7.1.5.1 Small-loop frequency range and band

The small-loop method provides a standard test procedure for the 9 kHz to 20 MHz range. It is recommended that the shielding be measured at a minimum of one frequency in each of the following bands: 9 kHz to 16 kHz, 140 kHz to 160 kHz, and 14 MHz to 16 MHz. Actual test frequencies shall be selected by the owner.

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[10] See Annex B.

These procedures are extendable down to 50 Hz provided the loop will fit inside the enclosure. At lower frequencies, it is anticipated that somewhat different equipment may be required to gain adequate dynamic range. For example, additional turns may be required on the receiver loop and/or transmit loop antennas or more power may be required depending on the SE of the enclosure.

7.1.5.2 Equipment and setup

Signal sources, measuring equipment, and arrangement shall be in accordance with the following sub sections and Figure 2. For smaller enclosures, it may be necessary to place the receiving antenna closer to the enclosure wall than 0.3 m. The 0.3-meter dimension was selected to provide coordination with this requirement in IEEE Std 299-2006 regarding test equipment. All equipment shall have written proof of current calibration in accordance with 4.3.

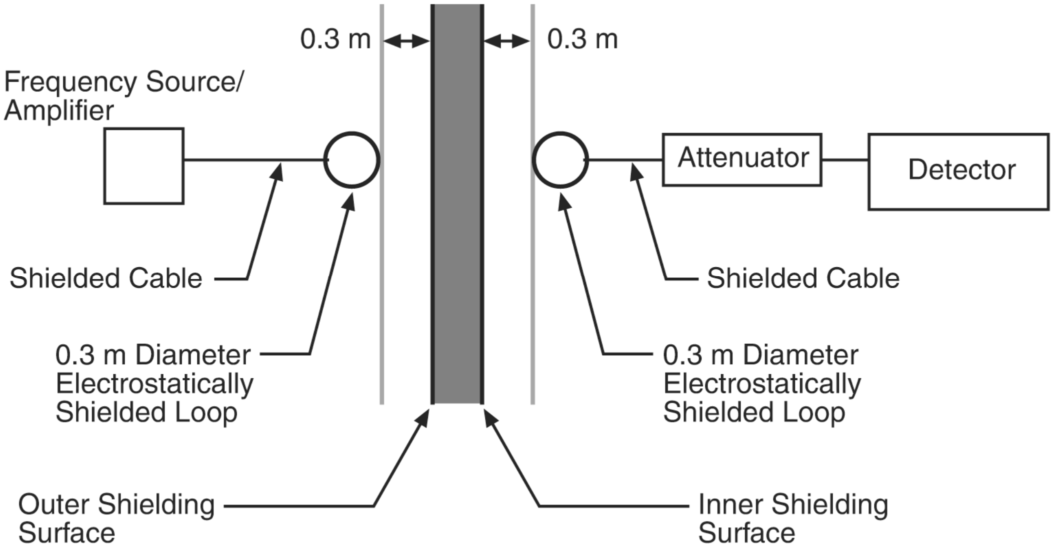


Figure 2—Dimensions of transmit (TX) and receive (RX) antennas (Source: IEEE Std 299-2006)

7.1.5.2.1 Source of magnetic field

The magnetic field shall be generated by a current in a 0.3 m diameter electrostatically shielded loop antenna. An ordinary audio frequency generator, plus amplifier, is usually adequate to supply the loop current if a suitable impedance matching device is used. Impedance matching may be needed to obtain the required dynamic range. A continuous wave (CW) signal without modulation shall be used to drive the antenna.

7.1.5.2.2 Receive antenna

The receive antenna shall be a 0.3 m diameter electrostatically shielded loop connected to a field-strength meter, spectrum analyzer, or similar device. For smaller enclosures, a smaller receiving loop may be required, as the maximum size of the loop diameter should not exceed one-third of the related dimension of the enclosure. In these cases, the loop should be positioned in the center of the enclosure.

7.1.5.2.3 High-permeability ferromagnetic enclosures

The nonlinear behavior of high-permeability ferromagnetic enclosures shall be considered before measuring shielding performance (see Annex D).

7.1.5.2.4 Shielding defects

Magnetic field testing in the 14 MHz to 16 MHz range is strongly recommended because of good sensitivity to shielding defects in this range. Problem areas shall be identified.

7.1.5.3 Reference measurements

The reference field (H_1) produced by the source in the absence of the shielding enclosure shall be obtained by direct measurement with the receiving loop spaced from the transmitting loop by 0.6 m edge to edge, or the same spacing to be used during the test if the receiving loop shall be placed closer than 0.3 m (see Annex D) plus the thickness of the shielding barrier, which is the total loop-to-loop distance that will be utilized when a shielding barrier interns. Both loop antennas shall be in the same plane (coplanar).

7.1.5.4 Measurement procedure

The measurements shall be made in accordance with Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, and Figure 8, with the transmitting and receiving loops each spaced by 0.3 m from the respective shielding barrier and coplanar in a plane perpendicular to the wall, ceiling, or other surface being measured. When testing the intersection of two surfaces, the antenna shall be orthogonal to both surfaces, as illustrated in Figure 7, and Figure 8. At each frequency and location, the generator output, which can be volts, watts, or a reference setting, shall be maintained at the value used during the reference measurement (see 7.1.5.3).

During all low-frequency measurements, one loop (typically the transmit loop) shall be maintained in a fixed position. The second loop (typically the receive loop) shall be reoriented the same as the transmission loop and displaced (physically swept laterally at least one-fourth the seam length on either side of the exact coplanar location) to seek a worst-case measurement. The maximum indication of the detector reading shall be used for determining the SE. Therefore, it is acceptable to position the external and internal loops only approximately coplanar when beginning the search for the worst-case measurement. However, the final measurement shall be made in the coplanar configuration.

7.1.5.5 Measurement locations

Around single-panel entry doors, small-loop tests shall be conducted for 14 loop positions, as indicated in Figure 3 and Figure 4, where H_d is the longest dimension. For enclosures where the longest dimension is 1 m or less, it is only necessary to make three measurements on each side. The plane of the loop shall be perpendicular to the line of the door contact being tested. For the horizontal portion of the door seal, the loop shall be at the corners and equidistant from the edges. For the vertical contact regions, the loop centers shall be located at the corners and at one-third the distance from both the top and the bottom. The top and bottom vertical contacts shall be measured as indicated in Figure 4. In Figure 4, an enclosure door is depicted to show relative positions. This door can be on the floor or on the top of the enclosure.

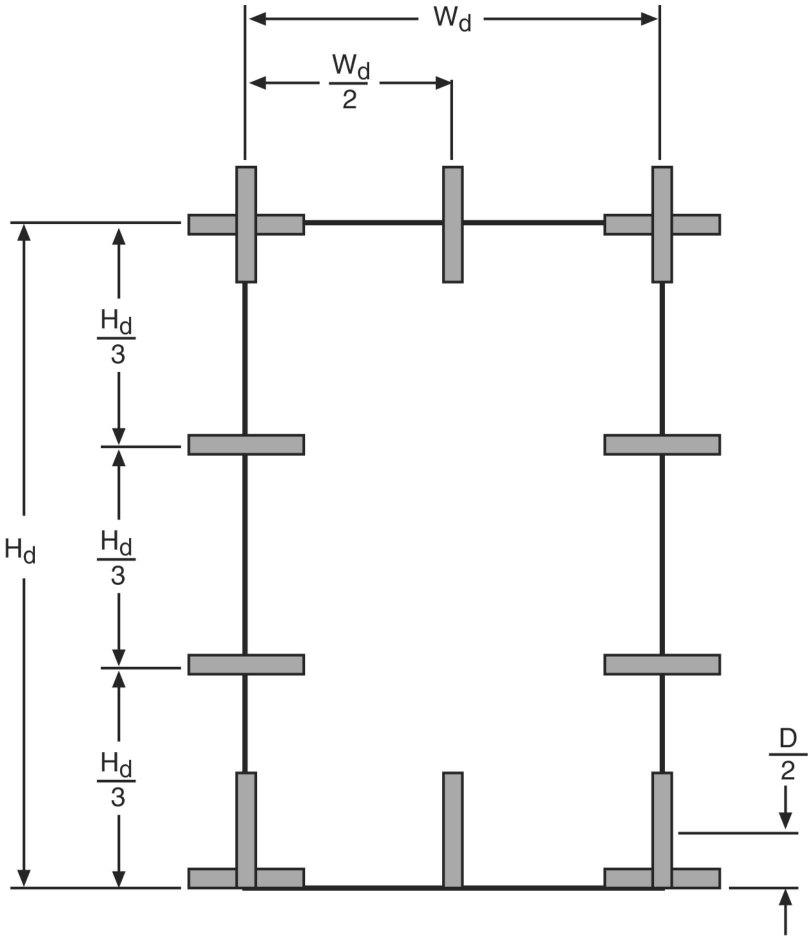


Figure 3—Measurement locations for a single door (Source: IEEE Std 299-2006)

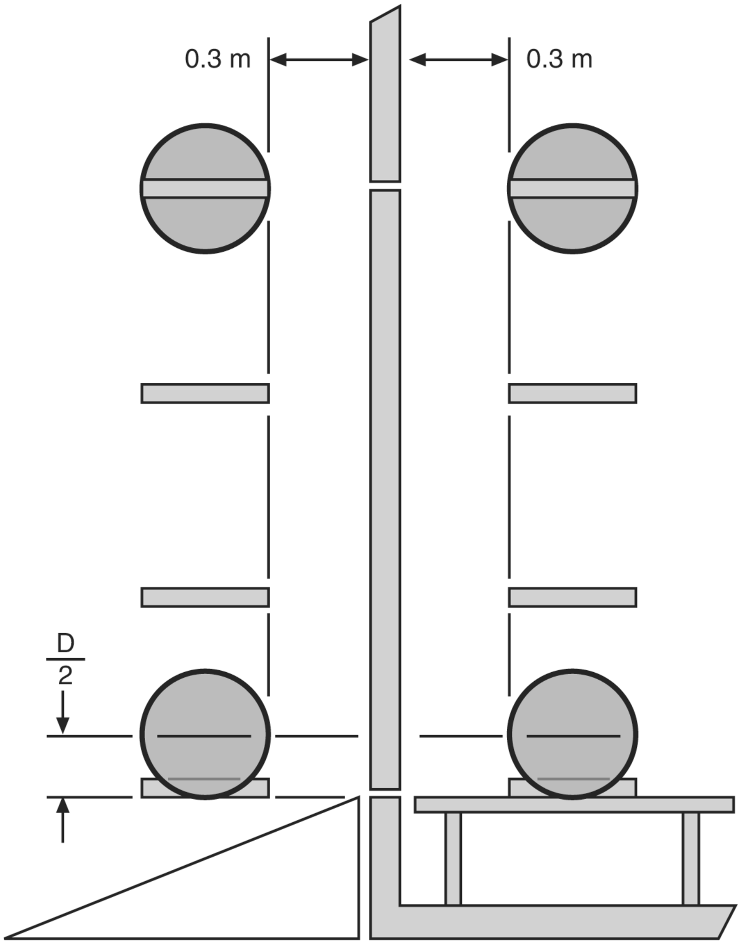


Figure 4—Door measurement locations (Source: IEEE Std 299-2006)

For multiple panel doors, the above test positions apply to each door as illustrated in Figure 4 and Figure 5. For doors with dimensions less than 1.5 m × 1.5 m, test positions may be dropped, provided that the spacing between test points does not exceed 1 m. In the region of panel-to-panel seams, shielding enclosure construction is electrically non-uniform. Non-uniformities include regions where modular portions are joined together by a clamp or bolt assembly (or by staples for a foil-type shield), or by a soldered, brazed, or welded joint. Measurements shall be conducted in a similar manner to those around doors, except that the centers of the loops shall be located only at the midpoints of each seam or joint, whether horizontal or vertical, as in Figure 6. In cases where the panel seams, whether bolted or welded, cannot be seen, attempts shall be made to determine the seam locations or panel sizes using applicable construction drawings or other documents. The test positions of Figure 6 shall be used for as much of the shield area as can be accessed for testing if the intervening non-shield materials are close enough to the shield to maintain the specified coupling distance between the loop antennas and shield proper. Measurement distances for door locations and seams may or may not be symmetrical.

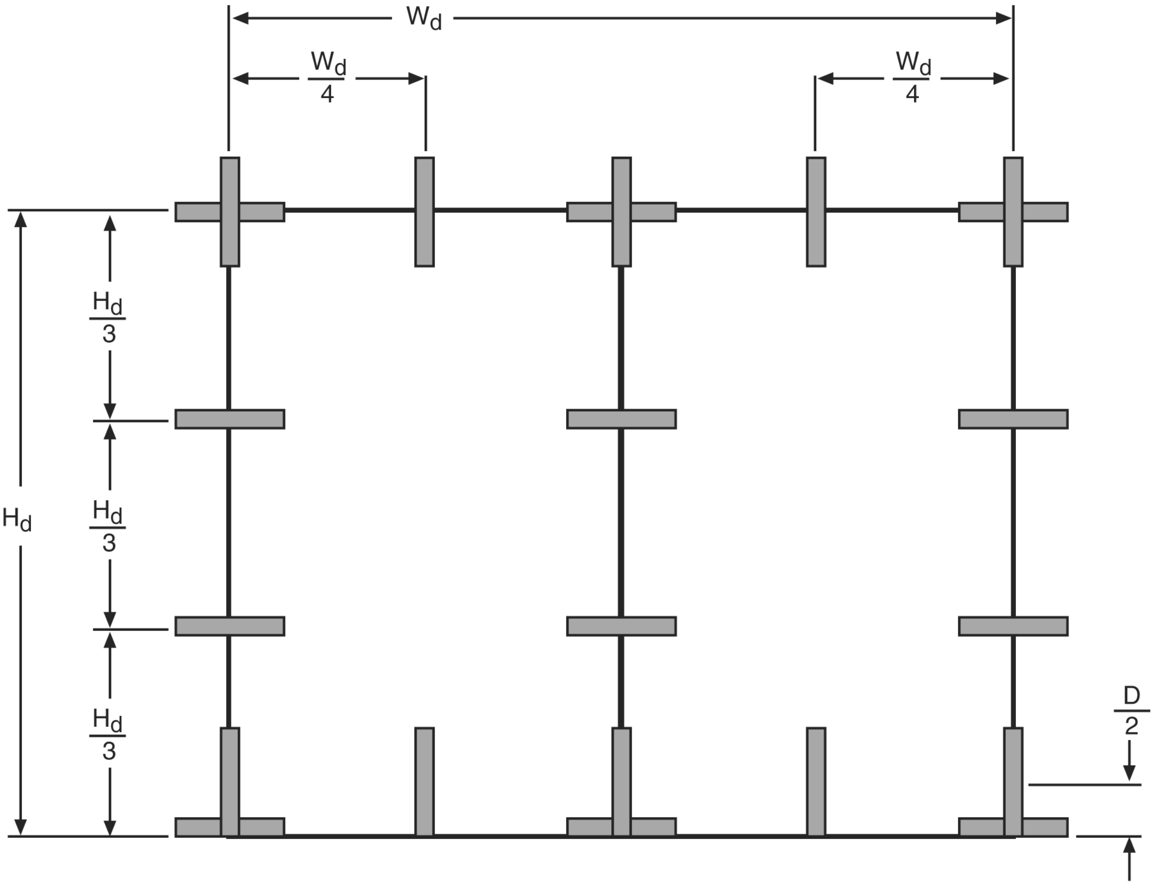


Figure 5—Measurement locations for a double door (Source: IEEE Std 299-2006)

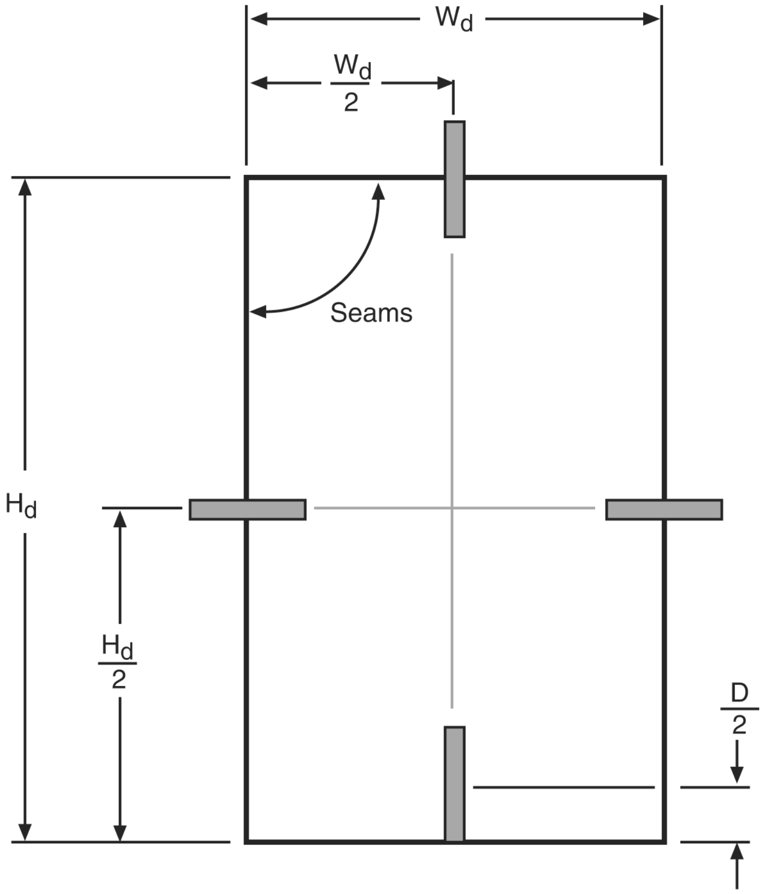


Figure 6—Panel seam measurement locations (asymmetrical) (Source: IEEE Std 299-2006)

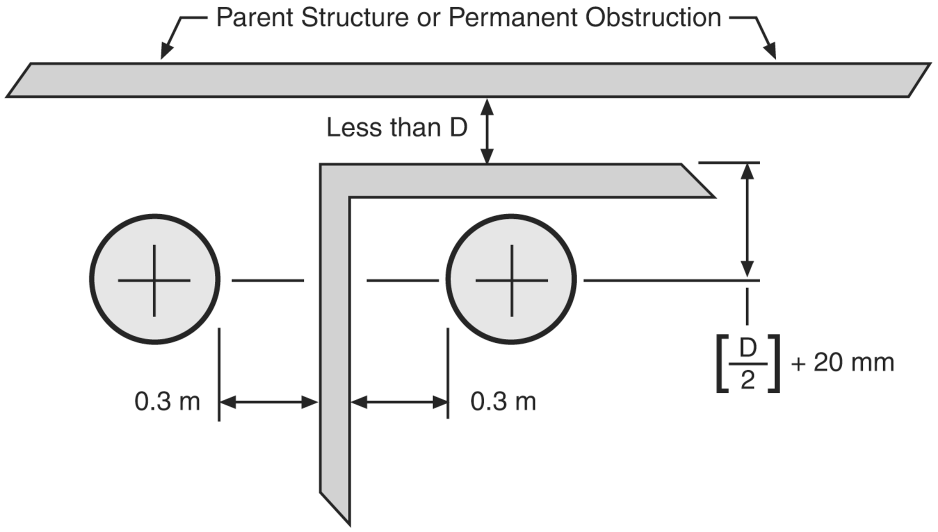


Figure 7—Partially accessible corner seam measurement locations

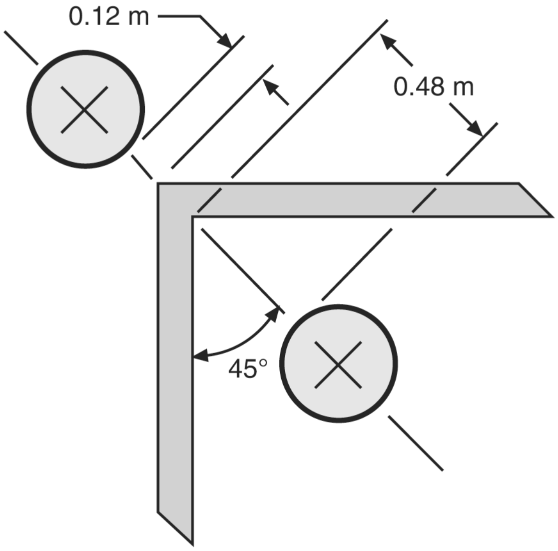


Figure 8—Fully accessible corner seam measurement locations (Source: IEEE Std 299-2006)

The performance of an accessible corner seam shall be measured as shown in Figure 8. Where the corner is not fully accessible or the receiving loop cannot be placed as shown, the arrangement shown in Figure 7 may be used. Each accessible panel shall be tested.

Shielding performance at an air vent, access panel, or connector panel is measured similarly to a seam. For an air vent, the plane of the loop shall be perpendicular to: 1) The panel containing the air vent, and 2) Each seam formed between that panel and the air vent. The extended plane of the loop should pass through the midpoint of the seam or as close to the seam as possible. If also possible, the edge of the loop shall be located 0.3 m from the panel. Ancillary equipment that attach to openings in the enclosure (such as blowers and fans) normally present during operation of the enclosure shall remain in place during the test. Other equipment that is not a normal part of the enclosure shall be removed prior to test.

For a single or small number of coaxial feed-through connectors, a single test position shall be satisfactory.

The shielding performance at power-line, signal-line, and control-line filters shall be measured. Each filter cabinet or filter box shall be tested at the penetration through the enclosure, and at non-soldered or non-sealed seams in the applicable case.

7.1.5.6 Determination of low-range shielding effectiveness

The shielding effectiveness shall be computed using Equation (B.1) or Equation (B.2) (also shown in Table 8), when linear units are used for measurement, or Equation (B.4) or Equation (B.5) (also shown in Table 8) when all meter readings are logarithmic in decibels.

7.1.6 Resonant range measurements: 20 MHz to 300 MHz

The resonant frequency range is not covered by this standard.

7.1.7 High-frequency measurements (non-resonant)

The high-frequency procedure directly measures the effect of high-frequency sources at positions over all accessible surfaces of the enclosure. The fields impinging on the shield shall be as planar as the relative wavelength and surrounding structure allows.

7.1.7.1 Frequency range and band

This section provides a standard test procedure for the non-resonant range. Actual test frequencies shall be selected by the owner and included in the approved test plan. In all cases, the lowest test frequency in this procedure shall be at least three times the lowest cavity resonant frequency of the enclosure, as determined by the method in 7.1.7.2 and Figure 9. Recommended frequencies for shielding measurements are a single frequency within each of the bands listed in Table 6.

These procedures shall be extendable up to 100 GHz with the substitution of the appropriate equipment.

7.1.7.2 Test equipment and setup

Signal sources, measuring equipment, and arrangement shall be in accordance with the following sections and Figure 10, Figure 11, and Figure 12. The resonant frequencies, measured in megahertz, for a six-sided rectangular or square enclosure are determined by Equation (5):

$$f_r = 150\sqrt{\left(\frac{1}{a^2}+\frac{1}{b^2}\right)} \tag{5}$$

where *a* and *b* are the two largest dimensions of the enclosure, measured in meters. Resonant frequencies for enclosures other than six-sided figures would need to be calculated by the investigator of that enclosure.

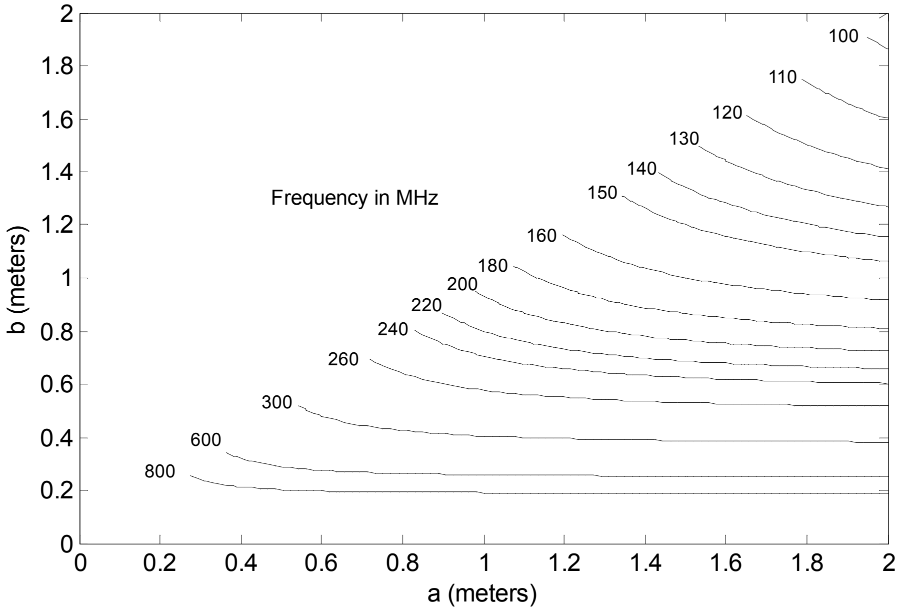


Figure 9—Resonant frequencies in MHz

7.1.7.3 Source of electromagnetic fields

The sources of electromagnetic fields shall be dipoles, biconical antennas, horns, yagis, log periodic, or other linear antenna types. A continuous wave (CW) signal without modulation shall be used to drive the antenna. Antenna locations are shown in Figure 10 and Figure 11.

To provide adequate dynamic range, it may be necessary to use very high power ultra-high frequency (UHF)/microwave sources. Care shall be taken to limit personnel exposure to hazardous RF field levels.

WARNING

For all measurements undertaken as a part of this standard, care shall be taken to protect personnel from potentially hazardous RF field levels (IEEE Std C95.1-2005). This standard also suggests that authorization for transmit operation be obtained from the appropriate regulatory agency prior to activation of any transmitter. See C.2. Care shall also be taken to avoid interference with other electronic equipment operating in the vicinity.

In all configurations, the effects of antenna transmission lines shall be considered. For example, when using linear dipoles, the connecting transmission line shall be run perpendicular to the antenna for at least one wavelength.

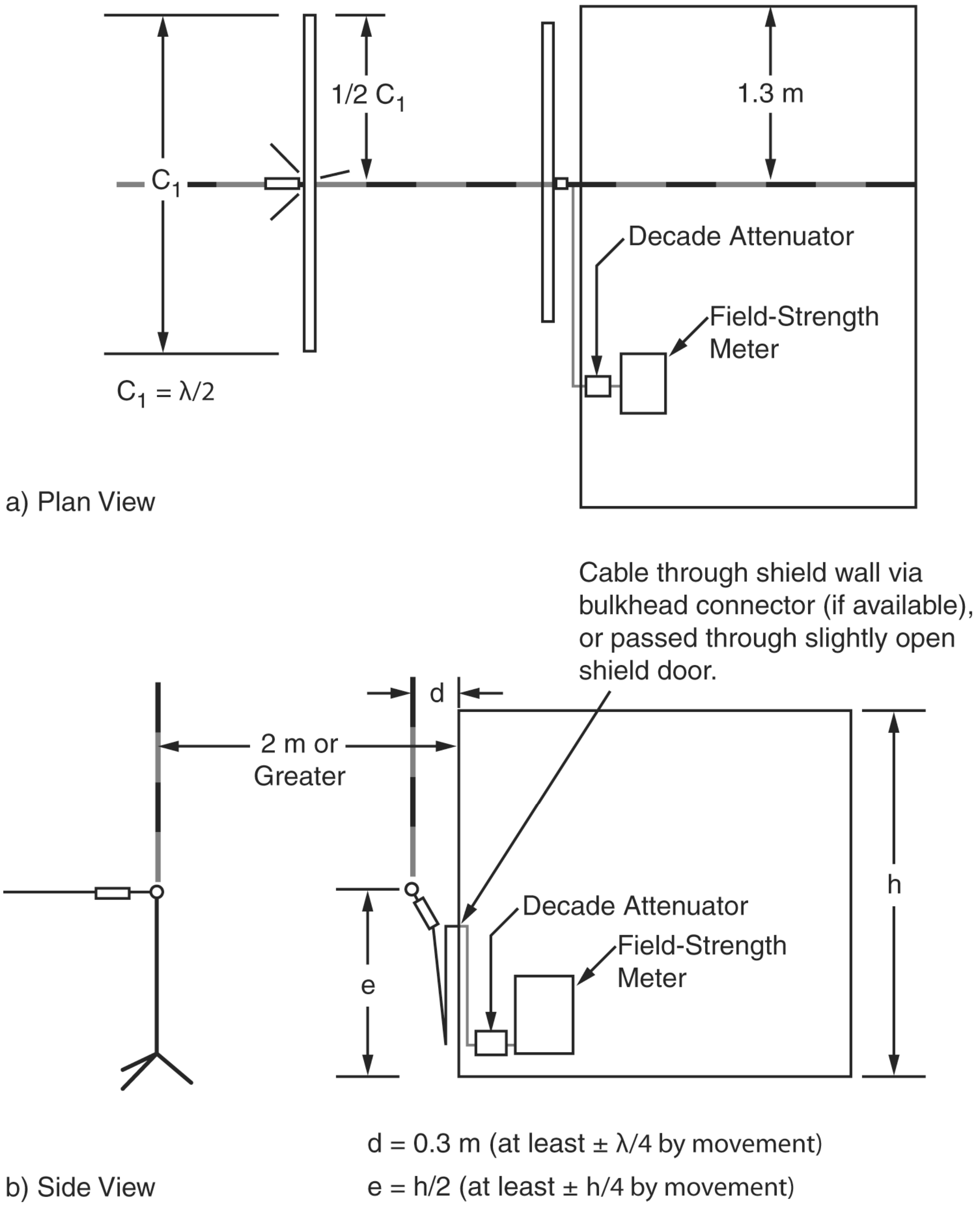


Figure 10 —Antenna locations for reference measurements (Source: IEEE Std 299-2006)

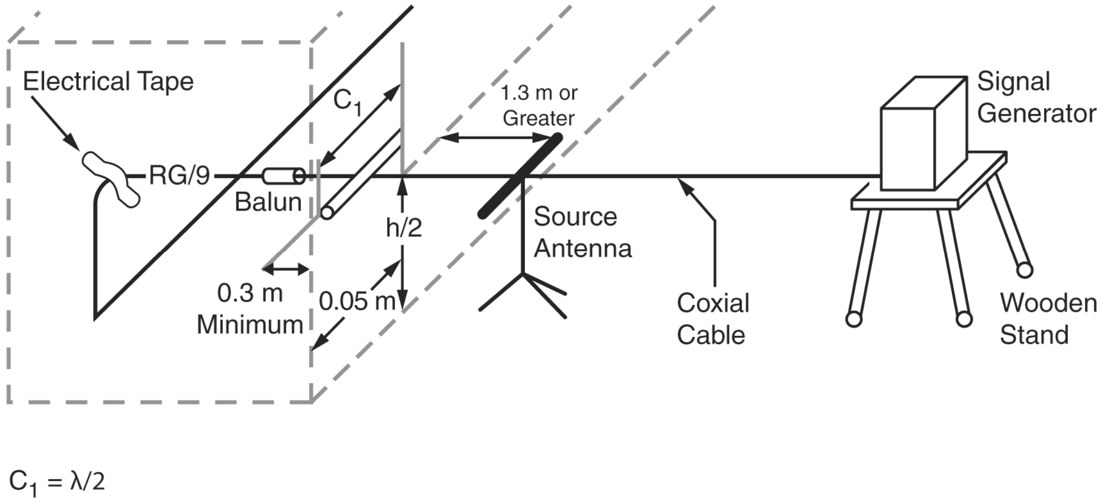


Figure 11—Movements of antennas (Source: IEEE Std 299-2006)

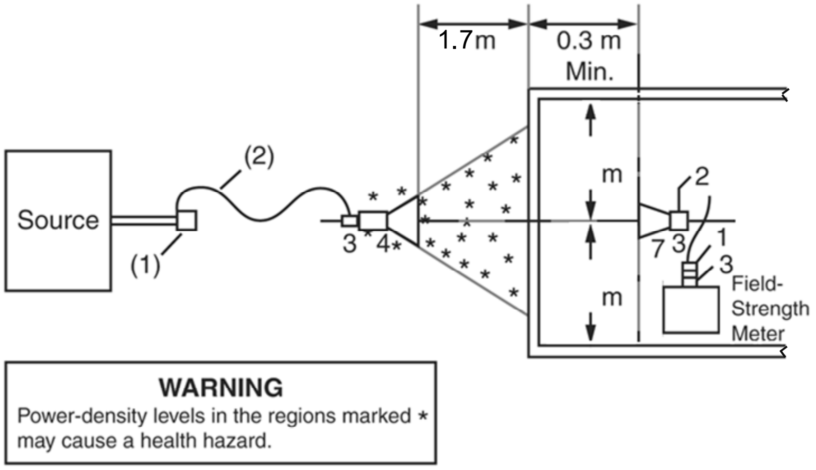
7.1.7.4 Electromagnetic field detection instrumentation

The field-strength measuring device shall be a field-strength meter, a spectrum analyzer, or similar.

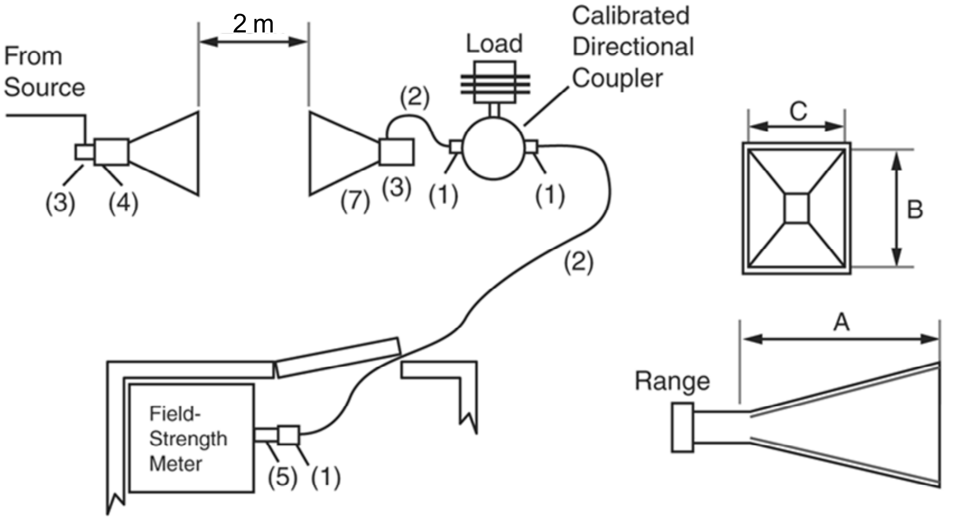
7.1.7.5 Electromagnetic field detection measurement antennas

In the range 110 MHz to 1 GHz, an electric dipole whose overall length is 1/2 λ is required. Its output shall be connected through a balun transformer via coaxial cable to a field-strength measuring device. The cable shall be perpendicular to the axis of the dipole for a distance of at least 1 m if allowed by enclosure dimensions. For smaller enclosure, the cable should be perpendicular to the axis of the dipole and shall be fixed to the facing wall with an electrically conducting tape.

A standard gain horn shall be used at frequencies above 1 GHz. For this standard, non-ridged rectangular waveguide horn antennas shall be used. Typical horn configurations are shown in Figure 12 (a through c) and typical dimensions are shown in Table 9. Further research is needed to address frequency ranges not covered in Table 9. For smaller enclosure, a smaller antenna may be required as the maximum size of the antenna should not exceed one-third of the related dimension of the enclosure. In this case, the antenna should be positioned in the center of the enclosure.



a) Broad-Area Microwave Penetration



b) Enclosure Free-Field Simulation

c) Standard Gain Horn Dimensions

NOTES
1-Type N adapter coax to waveguide(if needed).
2- Coaxial cable or waveguide.
3- Adapter (if needed).
4- Transmitter antenna, Table 9, or non ridged horn
5- Attenuator (if not within field strength meter).
6- Additional conterlines so that all areas are illuminated
7- Receiving horn antenna, Figure 12c, and Table 9, dimensions related to standard EIA waveguides, flanges, and waveguide-to-coaxial transitions.

Figure 12 —Horn antenna locations (Source: IEEE Std 299-2006)

Table 9—Dimensions[11] and frequency ranges for horn antennas

Frequency Range in GHz	Dimension A, Minimum (mm)	Dimension B, Approximate (mm)	Dimension C, Approximate (mm)
0.96 to 1.46	1,033	632	475
1.12 to 1.7	883	534	402
1.7 to 2.6	416	340	260
2.6 to 3.95	400	235	175
3.95 to 5.85	264	157	116
5.85 to 8.2	200	116	86
8.2 to 12.4	126	76	58

7.1.7.6 Preliminary procedures

Before formal testing, the testing organization is encouraged to test for leaks in the shield (and repair them) in accordance with the recommended procedures of Annex E. However, this preliminary check is not a mandatory part of the standard.

7.1.7.7 Reference measurement

Measurement of the reference level shall be made in accordance with the following sections and Figure 10 and Figure 12.

7.1.7.7.1 Reference measurements for dipole antennas (300 MHz to 1 GHz)

The reference field without the presence of the shield is measured by the following method. This method is designed to be conducted within typical facilities housing shielding enclosures and with a minimum reliance on long-term calibrations as illustrated in Figure 10.

The antennas shall be separated by a distance of 2 m, minimum, unless physical spacing limitations for either the reference level or SE readings preclude maintaining that spacing. In that event, maximum available separation shall be used, but shall not be less than 1 m, and that separation noted on the test report and data sheets.

The coaxial cable to the detector antenna (dipole) shall be kept perpendicular to the axis of the dipole for a distance of at least 1 m, except in the immediate vicinity of the shielding enclosure. The cable from the receive antenna is preferably routed through the wall of the shield via a bulkhead type of coaxial connector.

If this is not possible, it may be routed through a shield door that is only opened far enough to pass the cable. If it runs through the shield door, a check for direct coupling to the field-strength meter equipment shall be made by putting a dummy load in place of the receive dipole and verifying that any signal present is at least 10 dB below the reference reading.

With horizontal polarization for both antennas, the receiving dipole shall be moved vertically at least h/4 from the initial position. It shall also be moved 1/4 λ away from and towards the source. With vertical polarization for both antennas, the receive dipole shall be moved laterally at least one-fourth of the wall width. It shall also be moved 1/4 λ away from and towards the source. The maximum reading shall be noted and recorded as the reference level.

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[11] See Figure 12c. The dimensions listed are intended for guidance in the event antennas will be self-constructed, or for use in selecting available commercial equivalents.

7.1.7.7.2 Reference measurements for horn antennas (above 1 GHz)

The reference measurement shall be made in accordance with Figure 12b.

The attenuator and Type N adapter, if used, associated with the field-strength meter shall remain within the enclosure, and the receive antenna shall be placed at a distance from the enclosure wall in such a way that both antennas can be collinearly located with a physical separation of 2 m, unless physical spacing limitations for either the reference level or SE readings preclude maintaining that spacing. In that event, the maximum available separation shall be used, but shall not be less than 1 m, and that separation noted on the test report and data sheets. A feed-through bulkhead connector, installed in the wall of the enclosure, may be utilized to connect the output of the directional coupler to the transmission line, which connects the antenna to the field-strength indicator during the penetration measurement.

The height of both antennas shall be approximately the same as will be used during the measurement procedure. The output of the receiving antenna is connected via suitable transmission line. During the recording period, the receiving antenna shall be moved at least 1/4 λ in all directions and the maximum amplitude recorded.

7.1.7.8 Detailed measurement procedures for high frequency

The basic measurement procedure consists of positioning a transmit antenna outside the shield and a receive antenna inside the shield and measuring the magnitude of the largest received signal. The detailed procedures are the same for dipole and horn antennas.

7.1.7.8.1 Transmitter configuration

Following the procedures in Figure 12a, a series of transmit antenna positions and polarizations shall be selected to cover various surfaces of the shield in accordance with the approved test plan (see 4.2).

Horizontal polarization and vertical polarization shall be required. The center of the antenna shall be positioned at one-half the wall height above the floor. The transmit antenna shall be positioned at least 1.7 m, less the thickness of the shield, from the test surface, and shall maintain at least 0.3 m clearance from the floor. If physical space limitations have resulted in a reference measurement at less than 2 m, then the transmit antenna shall be positioned at the reference distance minus 0.3 m. For smaller enclosure, the antenna should be positioned in the center of the enclosure.

The power to the transmit antenna shall be the same as the power used in establishing the reference level in accordance with 7.1.7.7.

7.1.7.8.2 Receiver locations and data collection

The receiver antenna shall be swept in position (throughout the shield interior), in all directions of reception, and in polarization, to obtain the largest receiver response. The largest receiver response shall be recorded for determining the (minimum) SE. A minimum spacing of 0.3 m from the shielding surface to the closest point of the antenna shall be maintained. For smaller enclosure, the antenna should be positioned in the center of the enclosure.

7.1.7.8.3 Test points

The procedure of 7.1.7.8.2 for the receive antenna shall be repeated for all transmitter locations and all frequencies, and for all shield surfaces in accordance with the method selected from the approved test plan (see A.4). Test personnel are encouraged to choose the order of test param (frequencies, antenna locations) to minimize the test time. This may require that the antenna be swept inside the enclosure. A stepped antenna sweep may also be used. Test personnel may elect to be inside the shielded enclosure, but outside of the enclosure under test is preferred.

7.1.7.9 Determination of shielding effectiveness

The shielding effectiveness shall be computed by Equation (B.2) (also shown in Table 8), when linear units are used for measurement, or by Equation (B.3), Equation (B.5), or Equation (B.6) (also shown in Table 8) when all meter readings are logarithmic in decibels.

7.2 Part II – Physically small (< 0.75 m) and electrically large enclosures

This section describes the basic and detailed test procedures for measuring shielding effectiveness for physically small (< 0.75 m) and electrically large enclosures. Although the procedures are defined, this standard does not define or specify the measurement frequencies—start, stop, or span frequencies. Because the level of shielding effectiveness that is acceptable for any type of shield depends upon several factors, including the allowable amount of electromagnetic energy inside the shielded enclosure and the type of shielding materials used, this standard also does not define how much shielding effectiveness constitutes a pass or fail criteria for the shield. This criterion is left up to the designer or owner of the shield, shielded enclosure, or shielding material.

7.2.1 Basic procedure – single port

This sub-section describes the basic test procedures for determining shielding effectiveness measurements. Although no measurement frequencies are required by this standard, selected frequencies are recommended to the designer or owner of the shield for determining the shielding effectiveness of the enclosure under test. Selected frequencies should be based on the physical size of the enclosure. Successful tests at these frequencies should provide very high confidence that an enclosure provides the specified shielding effectiveness at all the frequencies covered by this standard.

The basic method for mathematically defining the shielding effectiveness of any enclosure is defined by Equation (6):

$$SE = -10Log_{10}\left(P_{in} / P_{out}\right) \tag{6}$$

where P_{in} and P_{out} are the received power levels from antennas inside and outside the enclosure, respectively.

Measuring the shielding effectiveness of small enclosures poses various problems. The first problem is associated with the internal resonances of the enclosure. This problem occurs with the measuring of shielding effectiveness for any size enclosure, both physically large and small. Because of the resonant nature of the fields inside a shielding enclosure, the fields have an internal modal structure, and, as a result, measurement of the fields inside the enclosure is a function of the location where the measurement is performed.

For large enclosures, two basic approaches are used to overcome this issue. One approach is to sample the field at various locations in the enclosure and then take some type of average value of the power level inside the enclosure. This is basically the approach taken in 7.1 of this standard. However, this is not practical for “truly” physically small enclosures because moving a probe throughout the volume of a small enclosure would be problematic. The second approach is based on a nested reverberation chamber technique (IEC 61000-5-7), which is typically done with mode stirring. However, placing a probe (or antenna) in the center of the small enclosure as is done in IEC 61000-5-7 poses difficulties. In addition, using conventional paddle mode stirring in a small enclosure would be problematic as well. That is, in most applications of measuring the shielding effectiveness of small enclosures it may not be possible to place a small mechanical stirring device inside the enclosures.

A frequency-stirred reverberation chamber approach overcomes these issues (see IEC 61587-3, Ed. 2 and [B14] for details). This procedure assumes that the enclosure is physically small (less than 0.75 m in the linear dimension), but electrically large (defined below).

A diagram of the proposed approach is shown in Figure 13. The basic approach is to place the small enclosure in a reverberation chamber. This type of configuration is essentially a nested reverberation chamber as discussed in IEC 61000-5-7. In this setup, the source is placed inside the large reverberation chamber, and the reverberation chamber is sealed up. The source (e.g., horn connected to an RF signal generator) is then scanned over a given frequency range. Because some portion of the RF energy in the outer chamber will couple into the small enclosure, this causes frequency stirring of the RF energy in the small enclosure. As a result, all points in the small enclosure statistically have the same field levels for the data averaged over some bandwidth of frequencies [B15]. Hence, the problem of sampling location is resolved, without the need to have a paddle (or stirrer) in the small enclosure. A hybrid approach combining mechanical stirring in the outer chamber with frequency stirring can be applied also as described in [B7].

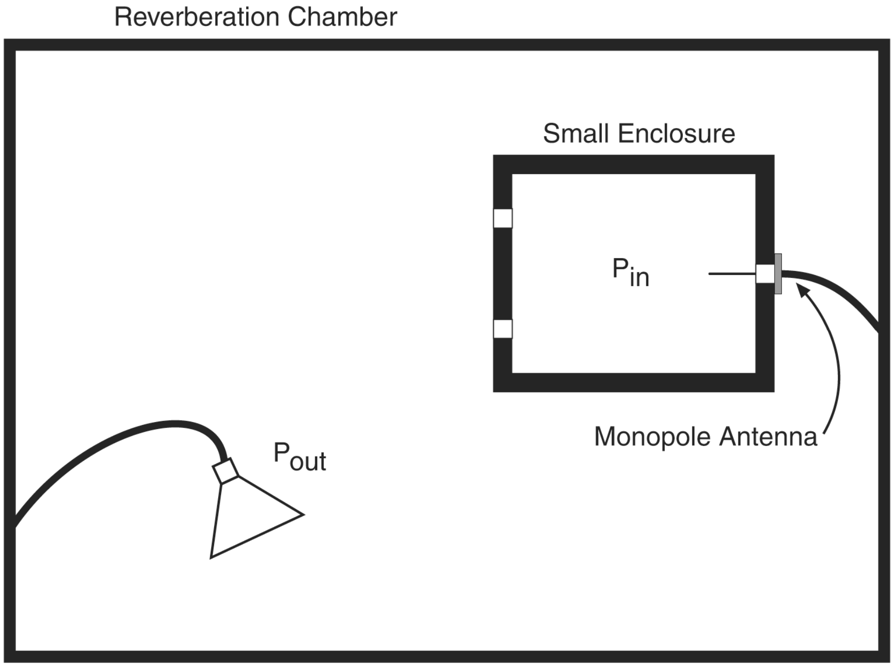

Figure 13—Illustration of the basic frequency-stirred reverberation chamber technique

WARNING

For all measurements undertaken as a part of this standard, care shall be taken to protect personnel from potentially hazardous RF field levels (IEEE Std C95.1-2005). This standard also suggests that authorization for transmit operation be obtained from the appropriate regulatory agency prior to activation of any transmitter. See C.2. Care shall also be taken to avoid interference with other electronic equipment operating in the vicinity.

The power levels in the small enclosure are monitored by a small monopole probe (or antenna) placed on one of the interior walls of the small enclosure. Holloway et al. [B14] and [B15] (see Annex F) have shown that the normal component of the electric field at the surface of a wall in a well-stirred cavity has the same statistics as a probe placed anywhere in the cavity. Thus, as long as the small enclosure is well stirred (i.e., through frequency-stirring), a small monopole probe placed on the inside wall will give the same average power level inside the small enclosure as that of an antenna placed in the center of the small enclosure. This frequency stirring in the outer chamber can be done with or without a conventional mechanical stirring processor in the large outer reverberation chamber. Using a combination of both frequency and mechanical stirring in the large outer reverberation chamber will improve the accuracy in the measurements.

7.2.2 Detailed procedure – multi-port

The more detailed frequency-stirred procedure for measuring shielding effectiveness is outlined below. The diagram for this experimental setup is detailed in Figure 14, which consists of placing the small enclosure (under test) in the outer large reverberation chamber.

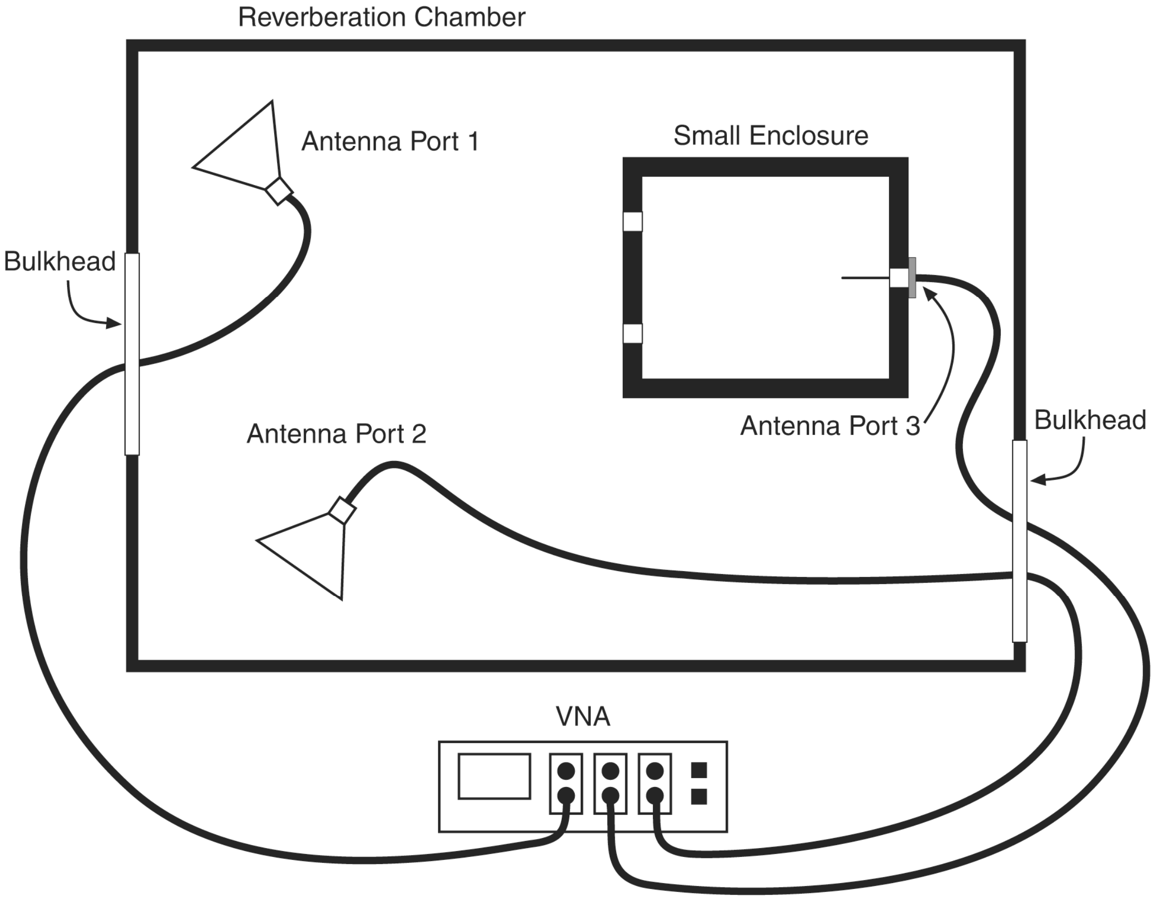

Figure 14—Measurement setup for determining SE of a small enclosure

In this approach, the power levels both inside and outside the small enclosure, and the ratio of these power levels, shall be measured for some input power injected into the large outer reverberation chamber. In order to excite the outer reverberation chamber and to monitor the power levels both inside and outside the small enclosure, three antennas are used. Note that these measurements could be performed with just two antennas (see discussion below), but the procedure will be explained assuming three antennas are used.

In order to monitor the power in the small enclosure, a small hole (sized appropriate for the monopole antenna) is drilled into one wall of the small enclosure (see the discussion in 7.2.7 on monopole location). A small monopole (see discussion in 7.2.5 on monopole antenna) is connected to one end of a 50 Ω coaxial cable. The monopole is inserted, from the outside, into the small hole of the small enclosure. The other end of the cable is connected to the bulkhead of the outer reverberation chamber. The monopole antenna is referred to as "Antenna Port 3" in Figure 14.

A second antenna is placed in the outer reverberation chamber in order to monitor the power in the outer reverberation chamber. This antenna is referred to as "Antenna Port 2" in Figure 14. A cable is connected to this antenna (Port 2) and the other end is connected to the bulkhead of the reverberation chamber.

A third antenna is placed in the outer reverberation chamber in order to excite energy into the outer reverberation chamber. This antenna is referred to as "Antenna Port 1 in Figure 14. A cable is connected to this antenna (Port 1) and to the bulkhead of the reverberation chamber. The two antennas in the outer reverberation chamber (Port 1 and Port 2) should be appropriate for the frequency range of interest (see discussion in 7.2.6).

A typical choice for these two antennas would be a ridge-horn antenna, but this is not required. The cables used to connect the antennas to the chamber bulkhead in this setup are assumed to be well shielded and certified for the frequency range of interest. Special attention should be given to the cable on the monopole since any leakage in this cable or its connectors will affect the dynamic range.

A multi-channel vector network analyzer (VNA) is connected via cables to the output ports of the reverberation chamber bulkhead. Before measurements are performed, a calibration procedure is required for the cables. This calibration is performed in order to transfer the reference plane to the input ports of the antennas used (see discussion in 7.2.10). The VNA used in these measurements could either be a two-port or four-port system.

7.2.3 Mathematical definition for multi-port detailed procedure

In this approach, the SE is defined as the ratio of the power levels inside to power levels outside the small enclosure and is given by Equation (7):

$$SE = -10\ Log_{10}\left(P_{in} / P_{out}\right) \tag{7}$$

Scattering parameter (S-parameter) measurements (using the multi-channel VNA) between Port 2 and Port 1 will give the power measured outside the small enclosure relative to the input power (Port 1), and S-parameter measurements between Port 3 and Port 1 will give the power measured inside the small enclosure relative again to the input power (Port 1). The ratio of these two S-param will give the SE of the small enclosure. With these S-parameter measurements, the SE as defined in Equation (7) can be expressed as Equation (8):

$$SE = \frac{\left\langle \left|S_{31}\right|^2 \right\rangle}{\left\langle \left|S_{21}\right|^2 \right\rangle} \frac{1-\left|\left\langle S_{22}\right\rangle\right|^2}{1-\left|\left\langle S_{33}\right\rangle\right|^2} \tag{8}$$

The $\langle\ \rangle$ represents the ensemble average (see 7.2.9), averaged over some frequency bandwidth (and paddle position if a combination of frequency and mechanical stirring in used in the outer reverberation chamber). Guidelines for the bandwidth (BW) for this averaging process are discussed in 7.2.8. The second term in this expression is required to correct for antenna mismatch issues (see the discussion in Annex G). Note when the correction due to S_{33} is not used, an underestimate of SE results. On the other hand, when the correction due to S_{22} is not used, an overestimate of SE results. This correction term approaches one for well matched antennas. The use of small monopole antennas in the small enclosure requires the denominator in this correction term. However, because one typically uses well matched antennas in the outer reverberation chamber, the numerator is approximately one.

A wall-mounted monopole antenna could also be used in the outer reverberation chamber for measuring the power levels as illustrated in Figure 15. If so, the mismatch correction in Equation (8) is still required. In general, even if the two monopole antennas are identical (the one on the outer chamber and the one on the wall of the small enclosure) $S_{22} \neq S_{33}$. This is because the small enclosure can influence the input impedance of the antenna at Port 3 and in turn cause S_{33} to be different from S_{22} even though the same monopole antenna is used at both locations.

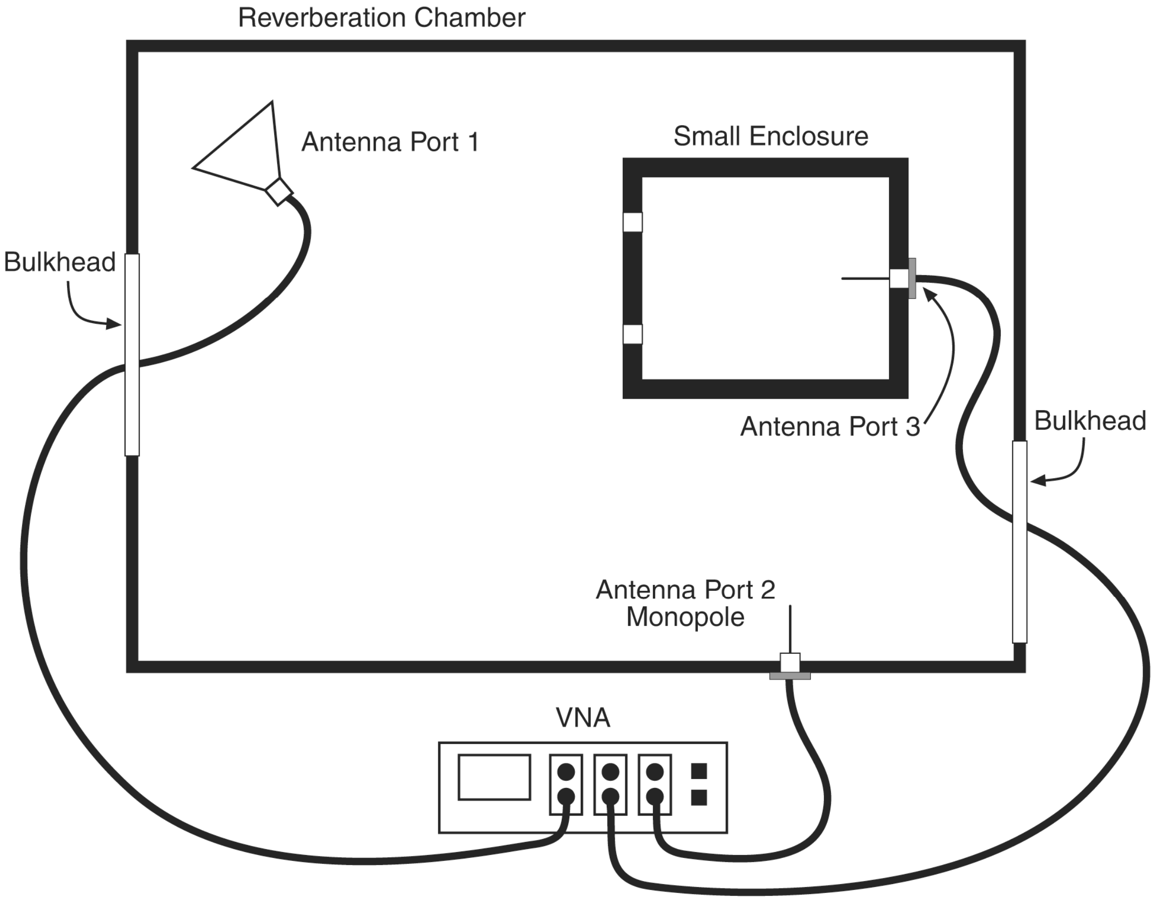

Figure 15—Wall-mounted monopole on the wall of the outer reverberation chamber

Besides using a wall-mounted monopole in the outer chamber, one could place a monopole in the working volume of the outer reverberation chamber in order to monitor the power outside the small enclosure (Antenna Port 2). In principle, this monopole could be the same monopole that is mounted on the wall of the small enclosure. However, care shall be taken to ensure that currents do not flow on the cable connected to Port 2 (this is further discussed in Annex H). If one wishes to use the same monopole to monitor the power both inside and outside the small enclosure, one shall remove the monopole from the small enclosure and mount the monopole on the wall of the outer reverberation chamber when conducting measurements. Figure 15 further illustrates this approach.

7.2.4 Alternative two-port approach

An alternative two-port approach can also be used. Using a VNA, one can measure the S-param between the source antenna (Antenna Port 1) and the monopole inside the small enclosure (Antenna Port 3). Next, use the same Number 2 port on the VNA, but connected to Antenna Port 2, and measure the S-param. These two measured S-param are used in Equation (8) to obtain the shielding effectiveness of the small enclosure.

7.2.5 Antenna used in small enclosure

The measurement procedure for Clause 7, Test procedures, Part II of this standard requires a small wall-mounted monopole antenna in the small enclosure. The measured SE should be independent of the size of the monopole antenna that is used, as long as the probe is calibrated correctly. This is only true for the short monopole probe; if the monopole probe becomes electrically large (the monopole length equals the wavelength of the frequency of interest), calibration and impedance mismatch correction will become difficult. The other requirement of the monopole length is associated with the enclosure size. If the monopole is too long, it can interact with other walls of the enclosure (walls different from the wall on which it is mounted on).

7.2.6 Antennas used in outer reverberation chamber

There is no general requirement for the antennas used in the outer reverberation chamber. It will depend on the size of the outer reverberation chamber and the frequency range of interest. Typically, one should use well matched antennas. However, the mismatch correction given in Equation (8) (also discussed in Annex G) compensates for the mismatch issue. In fact, the same type of small monopole used in the small enclosure could be used for the antenna to monitor the fields in the outer chamber. A wall-mounted monopole antenna could also be used in the large outer chamber for measuring the power levels (Port 2). However, as discussed in 7.2.2, the mismatch correction in Equation (8) is still required. With this in mind, it is good practice and highly recommended that a well matched antenna (for the frequency range of interest) be used as the source antenna (Port 1) for the outer reverberation chamber.

7.2.7 Location of monopole in small enclosure

In general, the measurement procedure in Clause 7, Test procedures, Part II of this standard is independent of the location where the wall-mounted monopole in located. However, there are a few guidelines that should be followed. If these guidelines are not followed, the wall-mounted probe may not measure the same power as that of a probe placed in the center of the enclosure, and as such, the accuracy of measured power inside the small enclosure comes into question.

The guidelines are as follows:

a) The monopole antenna should not be placed near a corner of the enclosure.
b) If possible, avoid locating the monopole antenna close to an aperture.

7.2.8 Guidelines for receiver bandwidth used in frequency stirring

There are some concerns with frequency stirring (or averaging) that require a brief discussion. The one main concern with frequency stirring is what BW should be used in the frequency averaging process. In choosing this BW, two criteria shall be met: 1) One based on a minimum BW, and 2) One based on a maximum BW.

The first criterion is based on a minimum allowable BW. There shall be significant modes in the enclosure such that there are independent frequency samples for the chosen averaging bandwidth. The number of modes in a BW needs to be much greater than unity [B15]. To achieve this, the BW shall satisfy the following (see IEC 61587-3, Ed. 2 for details) Equation (9):

$$\mathrm{BW} >> \frac{\mathrm{c}^3}{8\pi V f^2} \tag{9}$$

Where c is the velocity of light, V is the volume of the enclosure under test, and f is the center frequency in SI units.

This assumes that BW is somewhat greater than the single-mode bandwidth f/Q, f being the frequency and Q the enclosure quality factor, defined as the ratio of the energy stored to the energy per cycle. For large Q enclosure, generally it results BW greater that f/Q [B3].

The second criterion is based on a maximum allowable BW. There are two issues that one needs to be careful with when choosing the maximum BW. The first is associated with the shield property of the small enclosure under test. If the BW is too large, then resonances in the actual shielding response of the small enclosure would be smoothed out.

The second issue is associated with the outer reverberation chamber. If the BW is too large and the Q of the outer reverberation chamber changes significantly over that BW, then the frequency averaging approach is not valid. If the test environment (the outer reverberation chamber) is changing over this BW, the samples used for frequency averaging are not associated with the same conditions (i.e., the samples are un-correlated).

7.2.9 Ensemble average

In determining the shielding effectiveness, as defined by Equation (8), ensemble averages for both the through (S_{21} or S_{31}) and reflection (S_{22} or S_{33}) S-param are needed. There is a different averaging procedure for the through and reflection S-param, respectively. The ensemble average needed for through S-param (for example S_{21}) is given by Equation (10), with N given by Equation (11).

$$\left\langle \left|S_{21}\right|^2 \right\rangle = \frac{1}{N}\sum_{i=1}^{N} \left| S_{21}(f_i) \right|^2 \tag{10}$$

where

$$N = \frac{BW}{\Delta f} + 1 \tag{11}$$

where BW is the bandwidth used in this frequency averaging (or frequency stirring) approach (see 7.2.8), and Δf is the width of the frequency step used in obtaining the data. This averaging process requires taking the magnitude squared of the complex-valued S-parameter for a given frequency then summing over the frequencies in a given BW. A similar procedure is used to obtain $\left\langle \left|S_{31}\right|^2 \right\rangle$.

The ensemble average needed for reflection S-param (for example, S_{22}) is given by Equation (12):

$$\left|\left\langle S_{22} \right\rangle\right|^2 = \left| \frac{1}{N}\sum_{i=1}^{N} S_{22}(f_i) \right|^2 \tag{12}$$

This averaging process requires first summing the complex-valued S_{22} (this is a complex sum, i.e., adding real and imaginary parts) over the frequencies in a given BW, then taking magnitude squared of this average. A similar procedure is used to obtain $\left|\left\langle S_{33}\right\rangle\right|^2$.

7.2.10 Coaxial cable calibration

Losses in the coaxial cables need to be calibrated in order to remove these loss effects from the shielding effectiveness measurements. The test setup for the calibration is shown in Figure 16. This is essentially the same setup used in the shielding effectiveness measurements, with the exception that the cables that were connected to the input ports of the antennas are now connected to an electronic calibration device or individual calibration standards. At this point, a standard calibration is performed as defined for the specific model of vector network analyzer. This calibration transfers the reference planes of the S-parameter measurements to the input ports of the antennas used in the measurements.

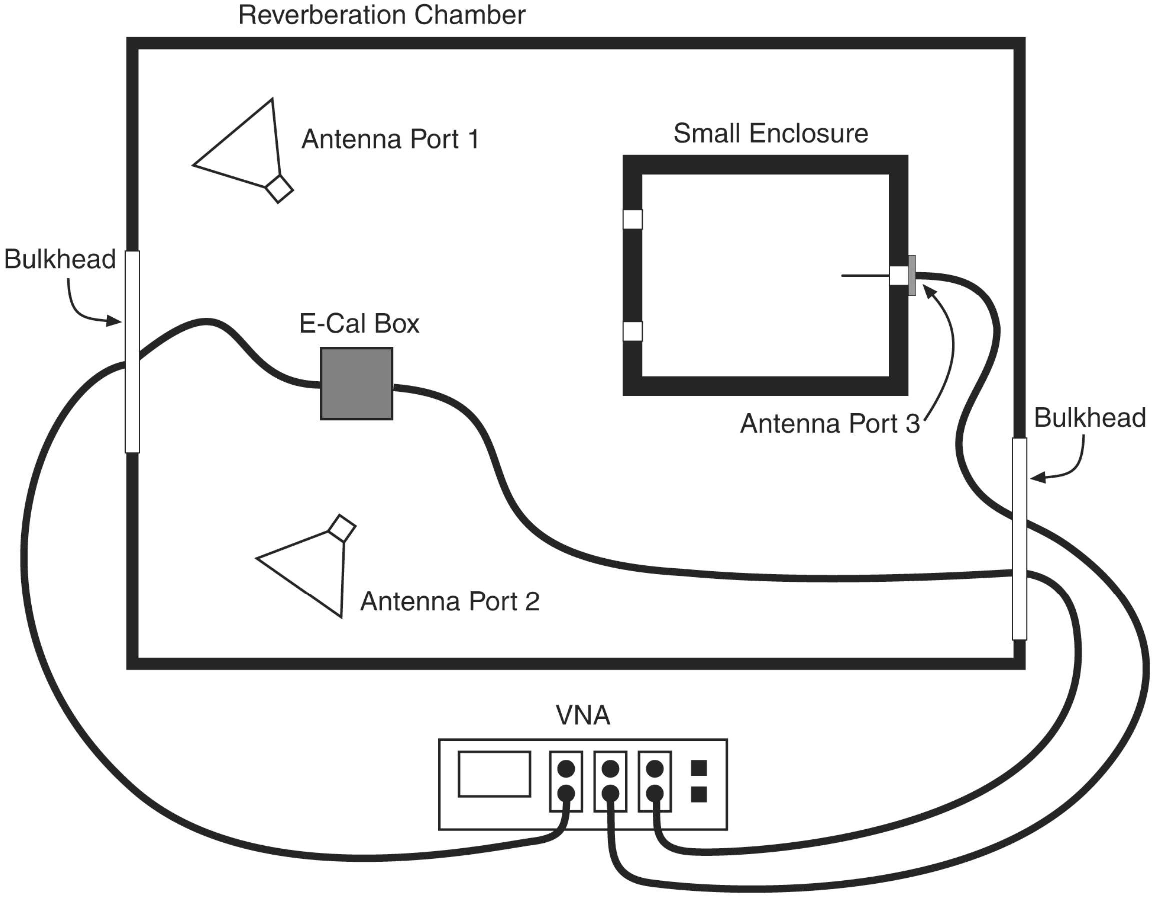

Figure 16—Set-up for coaxial cable calibration (The setup is for calibrating the cables connected to Antenna Port 1 and Antenna Port 2. A similar setup is used to calibrate the cable connected to Antenna Port 3.)

7.2.11 References

See Annex L for the references that pertain to Clause 7, Test procedures, Part II of this standard.

8. Quality assurance technical report

A technical report on the measurements performed in all parts of this standard shall be part of the requirements of this standard. However, the detail and the contents of the report shall be determined by the owner. Military users may use military standards or other detailed definitions of a test report at the owner's discretion. An abbreviated test report shall be the minimum reporting requirement of this standard. All reports shall be word processed. Equations and drawings may be done by hand if they are neat and legible.

8.1 Abbreviated test report

This report shall be prepared by the testing organization. As a minimum, the abbreviated test report should contain the following:

a) Name of the owner organization
b) Name of the testing organization
c) Brief identification of test enclosure by name
d) Location of test enclosure
e) Name of test personnel
f) Dates of test
g) Frequencies tested
h) Surfaces or faces tested
i) Shielding effectiveness measured

8.2 Full test report

If a full test report is to be prepared, it is recommended that the following content be included:

a) All of the information in the abbreviated test report
b) Reference to procedures used for the test
c) Diagram of the test setup(s)
d) Conclusions from the test data (pass/fail)
e) The material in 8.2.1, 8.2.2, and 8.2.3, below

8.2.1 Measurement procedure for full report

This is a description of the procedures followed for each part of the test.

8.2.2 Test instrumentation information for full report

Measurement instrumentation used shall be identified by manufacturer, model, serial number, calibration due date, and copy of the calibration document (supplied by the agency that performed the calibration), if required by the shield owner. There shall be complete schematic diagrams for all of the test setups that will enable a reader (an engineer) to understand how the equipment was connected.

8.2.3 Results for full report

Reported material shall include a full listing of test data. Included shall be copies of certified (signed) original data sheets or signed and change-protected electronic files of the original data, and a complete description of the computational method for determining the SE. Any modification to standard procedures shall be fully described in detail.

Reported material shall contain details of the test frequency selection process used if the frequencies used were selected to avoid interference to locally assigned frequencies. This report shall also include a full listing of the final SE values that were computed for the shield under test.

Annex A

(informative)

Rationale (for Part I – 0.75 m to 2 m enclosures)

A.1 Basis

The basis for this standard is a well-defined measurement method that combines technical validity with a minimum of testing in order to constrain the effort and associated costs involved. Such constraint is achieved by the following considerations, listed as they apply to the objectives of 1.2 of this standard.

A.2 Considerations pertinent to the objectives of 1.2 of this standard

A.2.1 Standard measurements

a) Measurement results within standard frequency ranges (Table 6) form a recommended uniform basis for comparing the performance of various shielding enclosures.

b) Standard measurement locations include the following:

    1) Preselected seam or join locations over the entrance wall; and

    2) Accessible locations of shielding penetrations over all the shielding surfaces.

A.2.2 Preliminaries

a) Prior to actual measurements, preliminary procedures are recommended to determine locations of poorest shielding performance. If such performance is inadequate, it may be improved before measurements of shielding performance are made.

b) For the low-frequency range, a procedure to measure electric-field shielding effectiveness is not provided, since experience with most enclosures has shown that the most stringent requirement involves the effectiveness of magnetic-field shielding.

A.2.3 Nonlinearity

Nonlinear effects may be significant in the presence of strong emissions, producing a change in shielding effectiveness. Hence, an optional procedure to determine significant nonlinearities over a specified exposure range is included in Annex C of this standard.

A.2.4 Extended frequency range

Additional measurement results may be obtained by following the recommended procedures and using any nonstandard frequency within these three frequency ranges:

a) Low: 50 Hz to 20 MHz

b) Resonant: 20 MHz to 300 MHz

c) 300 MHz to 100 GHz

A.3 Cavity resonances

Measurements in the range of frequencies at which the lowest, or fundamental, cavity resonance can occur for most enclosures shall consider variability of measurements. This frequency range is approximately $0.8\,f_r$ to $3\,f_r$, where f_r is the lowest cavity resonance frequency. Special precautions shall be observed when testing in this range.

A.3.1 Cavity resonance considerations

A shielded enclosure constructed of electrically conducting walls will function as a resonant cavity. Under certain conditions, if electromagnetic energy is injected into the shielded enclosure, standing waves will exist for frequencies above the fundamental resonant frequency f_r. As a result of the standing waves, the electromagnetic fields are not uniform within the enclosure and exhibit maxima and minima that depend on the frequency of excitation.

The frequencies and modes at which a shielded enclosure is resonant are determined by the geometry or shape of the shielded enclosure and its dimensions. Shielded enclosures of almost any shape can resonate, but mathematical analysis is generally limited to relatively simple cases such as rectangular, cylindrical, and spherical enclosures. Most shielded enclosures are essentially six-sided rectangular enclosures (parallelepipeds).

A lossless, six-sided rectangular enclosure can support resonances for frequencies at the resonant frequency given by Equation (A.1):

$$f_{ijk} = \frac{1}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\left(\frac{i}{a}\right)^2 + \left(\frac{j}{b}\right)^2 + \left(\frac{k}{c}\right)^2\right)} \tag{A.1}$$

where

μ is the permeability of free space inside the enclosure
ε is the permittivity of free space inside the enclosure
a is the longest dimension of the enclosure in m
b is the intermediate dimension of the enclosure in m
c is the shortest dimension of the enclosure in m

such that $a > b > c$ and i, j, and k are positive integers (0, 1, 2, 3, …). However, not more than one of i, j, and k can be zero at the same time. Under ideal conditions, the resonant frequency in MHz is given by Equation (A.2):

$$f_{ijk} = 150\sqrt{\left(\left(\frac{i}{a}\right)^2 + \left(\frac{j}{b}\right)^2 + \left(\frac{k}{c}\right)^2\right)} \tag{A.2}$$

Thus, the *lowest* resonant frequency for this shielded enclosure is calculated from Equation (A.3):

$$f_r = f_{110} = 150\sqrt{\left(\left(\frac{1}{a}\right)^2 + \left(\frac{1}{b}\right)^2\right)} \tag{A.3}$$

which is obtained by using indices $i = 1$ and $j = 1$ for the two longest dimensions, a and b, and using index $k = 0$ for the shortest dimension, c.

In principle, a shielded enclosure can sustain cavity resonances if the condition in Equation (A.4) is satisfied:

$$f \geq f_r \tag{A.4}$$

and a shielded enclosure cannot sustain cavity resonances if the condition in Equation (A.5) is satisfied:

$$f < f_r \tag{A.5}$$

For the maximum size shielded enclosure, with all three of the lowest-order modes (e.g., TM_{110}, TE_{011}, and TE_{101}) are degenerate and have the same resonant frequency for $a = b = 2$ m, expressed as Equation (A.6):

$$f_r = f_{110} = 150\sqrt{\left(\left(\frac{1}{2}\right)^2 + \left(\frac{1}{2}\right)^2\right)} = \frac{150\sqrt{2}}{2} = 106 \text{ MHz} \tag{A.6}$$

This is the lowest fundamental frequency because smaller enclosures will have a greater f_r. For enclosures with maximum linear dimensions between 0.75 m and 2 m the lowest fundamental resonant frequencies will lie in the range 283 MHz to106 MHz respectively.

The energy loss in a cavity is described by a quality factor, Q, which is the ratio of the energy stored to the energy lost per cycle. The energy loss in an empty shielded enclosure is a function of the electrical conductivity of the metal walls; therefore, minimum losses occur when highly conducting materials such as copper are used. Any material within the cavity that has a loss factor greater than air will increase the losses.

A.3.2 Slot resonance considerations

There are resonance effects other than cavity resonances that may affect the measured shielding effectiveness of the shielded enclosure. One such phenomenon is slot resonance. The penetration of electromagnetic fields through a given slot in a conducting plane varies with frequency. Slot resonance may occur at frequencies below the fundamental resonance frequency f_r for cavity resonance.

These resonance effects are inherent in the electromagnetic performance of the shielded enclosure and are not artifacts of the test technique; consequently, such resonance effects should be considered, as is the case with cavity resonance effects.

A.3.3 Procedural cautions

Empirical tests demonstrated that interconnecting cables between the antenna and detector do interact with existing fields in the enclosures and can have a significant effect on the measured SE values. For this reason, the use of antennas with baluns and cables employing ferrite loading has been mandated to minimize these effects. It is suggested that the tester use only the one longest length of connecting cable necessary for all testing inside of a given shielded enclosure. Using varying cable lengths can produce different measurement values within the same given enclosure and may make repeatability of results more difficult to achieve. The length of the cable used should be included in the test report.

Due to the nature of resonance effects, if there is reason to believe that such effects are a significant factor in the measured SE values of a shielded enclosure undergoing evaluation, then it may be necessary to perform either a frequency sweep (source and detector) from some point below the frequency of interest to some point above it. Alternatively, a series of discrete stepped frequencies may be used to reduce uncertainty and improve the confidence level of the measurement. An effect should be considered significant if variations of apparent SE value greater than 3 dB occur over this limited frequency span.

In general, resonant effects will be minimal below 0.8 f_r. Whenever possible, tests within this range should be conducted at or below 0.8 (80%) of the calculated fundamental resonant frequency for the given enclosure.

The performance of the receiving antenna can be affected by being located too near the enclosure metallic wall. Refer to Figure A.1 for guidance in positioning the receive antenna while making measurements.

In complex cavities, such as shielded enclosures excited at high frequencies (as defined in this document), the directivity characteristics of the antenna are lost. This, along with the enhancement of the fields by the quality factor or *Q* of the enclosure, results in the incorrect measurement of the fields within the enclosure. The definitions for shielding effectiveness given in this document do account for complex field conditions. Only Clause 7, Test procedures, Part I of this standard requires the use of standard gain antennas in order to obtain a consistent measurement methodology for obtaining and comparing the shielding effectiveness of enclosures.

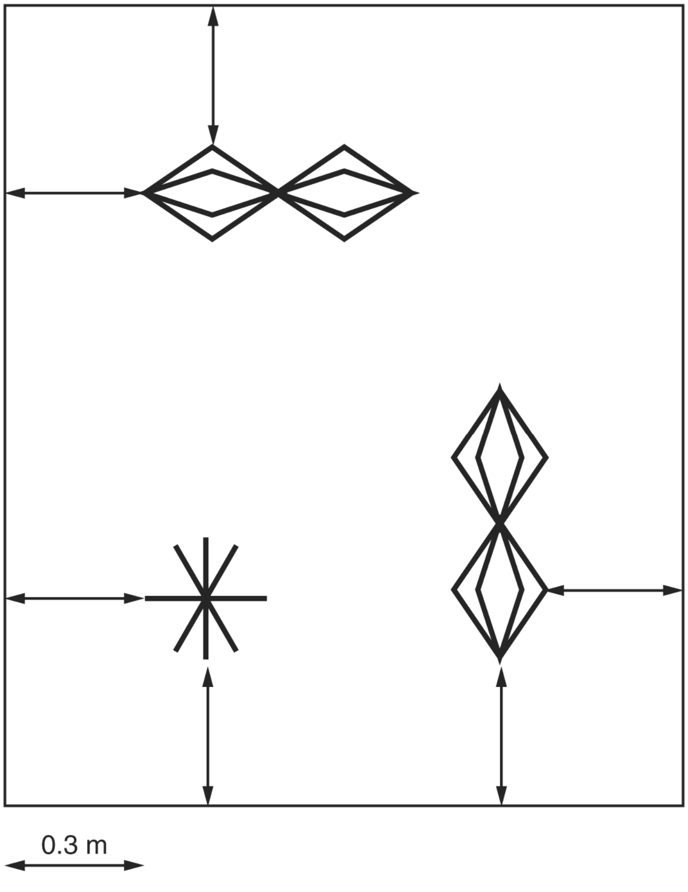

Figure A.1—Minimum spacing from closest tip of antenna to shielded enclosure wall

If correction for these effects is desired, then Equation (A.7) and Equation (A.8) can be used to calculate E_1 and E_2 for use in the equations contained in Table 8, respectively:

$$\left|E_1\right| = \sqrt{377 \cdot 4\pi \cdot \frac{P_r}{\lambda^2 G}} \text{ V/m reference measurement} \tag{A.7}$$

$$\left|E_2\right| = \sqrt{377 \cdot 8\pi \cdot \frac{P_r}{\lambda^2}} \text{ V/m reference measurement} \tag{A.8}$$

where

P_r is the power received in watts
λ is the wavelength in m
G is the numeric antenna gain

NOTE—The enclosure measurement assumes a free space impedance of 377 Ω as has been presented in several National Institute of Standards and Technology (NIST) Technical Notes. Work by NIST suggests that this is a close approximation. Subsequent work at NIST (detailed in a Correction Note to NBS Tech Note 10927) suggests that the maximum amplitude of the fields within the enclosure is more accurately predicted by using the average of the field magnitude. Some field level compression has been noted below about 1 GHz, and therefore this newer method may not be fully applicable in a general case. Use of the above expression for E_2 will yield an approximation within about 1 dB of the value obtained by assuming an impedance of 377 Ω.

A.4 Measurement locations

A.4.1 Locations for measurement around Device under Test (DUT)

Often, enclosures installed in buildings have one or two walls, in addition to the floor and/or ceiling, inaccessible for measurement purposes. Thus, making measurements along all surfaces of a shielded enclosure, although conceptually desirable, is impractical. A practical approach would be to measure all accessible surfaces. In considering economics, this would penalize the more accessible enclosure by requiring more measurements than a similar enclosure installed in a more restricted area. Practical field testing at the higher frequencies has shown that external reflections of radio-frequency energy can penetrate a poor seam or joint on the non-accessible side(s), resulting in reduced overall shielding effectiveness for the enclosure.

Therefore, these areas shall be checked in at least a non-direct illumination manner to verify the absence of significant leaks. For the vast majority of enclosures, all of the walls containing entrance doors are accessible, and are to be measured at specific locations by this standard.

In the case of enclosures having architectural treatments (including, but not limited to, drywall and/or insulation without metal backing, acoustical absorber, and studding, either wooden or metallic) that either partially or fully encase the entrance door wall, measurements shall be taken in accordance with the applicable procedure for the frequency range and the transmit and receive probes spaced to include the architectural treatments as part of the shield. Since entrance walls may not include all penetrations, measurements limited to entrance walls might not provide an equitable basis for determining the shielding effectiveness of all enclosures. Hence, all accessible wall areas in the immediate vicinity of penetrations are also required to be measured. (To the extent that some penetrations are inaccessible, the concept of indirect, reflective checks may be necessary to confirm the absence of leakage at penetrations that are not externally accessible.) Standard measurement locations are summarized in A.2.1b).

A.4.2 Effects of measurement location

Signal source area reflections exist with broad antenna apertures. When testing in non-anechoic enclosed locations it is good practice, if possible, to establish a baseline reference response curve for that location without the DUT present. If this cannot be done, comparable DUT data acquired in an ideal test location may define response variations.

A.5 Measurement equipment

Test procedures have been formulated 1) To enable the use of commercially available equipment for conducting tests under less-than-ideal conditions (such as within typical facilities used to house the shielding enclosure), and 2) To minimize changes in internal impedance of the antenna (due to proximity to the shield) from affecting the data measured.

Annex B

(informative)

Mathematical formulas (for Part I – 0.75 m to 2 m enclosures)

B.1 Specific mathematical formulations

In general, fields penetrating a shielding enclosure arise from both the electric and magnetic components of the electromagnetic energy impinging upon the enclosure. If the penetrating electric and magnetic fields are measured separately, each can be demonstrated to be a function of the impinging wave. In addition, the wave impedance of an applied field is radically altered upon penetrating an enclosure, and the measurements may be affected by the position of the sensor; measurement results may be sensitive to the test procedure details, unless the details are closely controlled. As a result, specific definitions for measures of enclosure performance are set forth in the following sections for each associated measurement procedure.

B.2 Low range (50 Hz to 20 MHz) shielding effectiveness

In the low range of frequencies (50 Hz to 20 MHz), the form for expressing shielding effectiveness in terms of magnetic field performance is given by Equation (B.1):

$$SE_H = 20\log_{10}\frac{|H_1|}{|H_2|} \text{ (dB)} \tag{B.1}$$

where

H_1 is the magnetic field measured using the antenna placed in the prescribed configuration in the absence of the enclosure (reference reading); and
H_2 is the magnetic field measured using the antenna placed in the prescribed configuration within the enclosure

When the meter readings V_1 and V_2 are, respectively, proportional to H_1 and H_2 (the usual measurement situation), a more convenient form for Equation (B.1) is given by Equation (B.2):

$$SE_H = 20\log_{10}\frac{|V_1|}{|V_2|} \text{ (dB)} \tag{B.2}$$

These expressions apply only to the specific measurement procedures described in 7.1.

where

V_1 is the voltage reading in the absence of the enclosure (reference reading); and
V_2 is the voltage reading within the enclosure.

B.3 High range (300 MHz to 100 GHz) shielding effectiveness

For the high range (300 MHz to 100 GHz), shielding effectiveness is expressed using Equation (B.6).

B.4 Nonlinear (logarithmic) calculations

When non-linear (i.e., logarithmic) measurement units are used, such as dBm or dBμA, Equation (B.3), Equation (B.4), Equation (B.5), or Equation (B.6) may be used to directly derive shielding effectiveness.

$$SE_E = |E_1|(dB) - |E_2|(dB) \tag{B.3}$$

$$SE_H = |H_1|(dB) - |H_2|(dB) \tag{B.4}$$

$$SE_V = |V_1|(dB) - |V_2|(dB) \tag{B.5}$$

$$SE_P = |P_1|(dB) - |P_2|(dB) \tag{B.6}$$

where

E_1, H_1, V_1, or P_1 is the reference electric field, magnetic field, voltage, or power intensity measured without the enclosure (in dBμV/m, dBT, dBV, or dBm); and
E_2, H_2, V_2, or P_2 is the electric field, magnetic field, voltage, or power intensity measured with the enclosure in place (in dBμV/m, dBT, dBV, or dBm).

B.5 Dynamic range considerations

The dynamic range (DR) of a test system is determined by the strength of the exciting signal, the performance of associated transmit and receive antennas, cable losses, attenuator and/or preamplifier performance, and the noise floor of the receiving instrument. As a practical matter, there is usually sufficient signal source power available for general applications (testing of enclosures with expected SE greater than 120 dB may require higher transmit power). The passive antennas required by this standard will not measurably affect the DR of the system.

Finally, except for long cables that may be required for testing very large enclosures, cable losses are not significant up to about 1 GHz. Thus, the receiving instrument and any preamplifiers become the important consideration in determining DR.

Modern receiving instruments typically exhibit noise floors below –120 dBm when filters of less than 30 kHz bandwidth are in use. The critical issue for DR, then, is maximum signal into the instrument without causing non-linearity (gain compression), which will skew reference level readings and affect SE values. The DR of the receive system (receiving instrument plus any external attenuators) is the difference between the largest possible input signal (usually defined as being at the 1 dB compression point) and the noise floor (which limits the minimum detectable signal). The DR for a receiver is expressed in decibels. Thus, the DR of a receiver is given by Equation (B.7):

$$DR_{RCVR} = P_1(dB) - P_2(dB) \tag{B.7}$$

where

P_1 is the minimum input signal that causes 1 dB compression (including internal and/or external attenuators); and
P_2 is the instrument minimum detectable signal (usually the noise floor) at the frequency and filter bandwidth to be used.

For purposes of determining DR for this standard, only an upper bound is needed, and DR shall only exceed anticipated SE by 6 dB. This means that the absolute DR, as determined above, does not need to be measured for an SE test unless a very high SE is expected for the enclosure. As long the receiving system is linear using the transmit power levels of actual testing during reference level measurement, and the DR (considering the receiver noise floor) exceeds the SE requirement by at least 6 dB in actual testing configuration, the requirements of this standard have been met.

Annex C

(informative)

Miscellaneous supporting information (for Part I – 0.75 m to 2 m enclosures)

C.1 Coplanar versus coaxial loops

Significant differences exist between currents excited on a shield surface by coplanar and coaxial loops. Coplanar loops cause current flow in the shield to be concentrated in one line lying in the plane of the loops. Coaxial loops cause current flow in the shield to be concentrated in the geometric shape of a circle parallel to the exciting loop. Three measurement considerations result from these differences:

a) *Location precision.* Defects at seams can be located more precisely from a current flow across the seam (coplanar case) than from a double current flow (coaxial case), which is especially important in the presence of multiple defects.

b) *Loop impedance.* The input impedance of a coaxial loop changes more drastically than a coplanar loop between the following two measurement situations: 1) In the presence of a shield, and 2) Away from the shield. A resulting effect on the source field strength is overcome in the measurement procedure by maintaining the same current in the source loop for the measurement situations.

c) *Source power.* The power required to drive the source loop is less in the coaxial case than in the coplanar case due to tighter loop-to-loop coupling. The use of coplanar loops is advocated in this standard on the basis of their precision in locating defects and in measuring their effects. Unshielded loop antennas generate and/or receive both magnetic and electric fields. Since the low frequency electric field component is reduced significantly more than the magnetic component, artificially high (4 dB to 10 dB) shielding effectiveness measurements are obtained with unshielded loops. Only electrostatically shielded loop antennas shall be used for this standard.

C.2 Nonlinearity of high-permeability ferromagnetic enclosures

Very intense magnetic fields may saturate magnetic materials and cause inaccurate magnetic field measurements. Nonlinearity effects may be determined by placing source and receiving loops on opposite sides of a panel near geometric center (as shown in Figure 2), and measuring the magnetic SE as a function of source strength. Generator output shall be increased in 10 dB steps, nominally 0.1 W to 1 W and 10 W. If the magnetic SE decreases more than about 2 dB, then intermediate level measurements shall be made. The results shall then be plotted to determine the highest level permissible for linear performance (within ±1 dB).

C.3 Selecting measurement frequencies

C.3.1 Regulatory note

Transmitter operation should be authorized by the appropriate regulatory agency. Permission from the appropriate regulatory agency should be obtained before activating any transmitter. In many cases, transmitting equipment shall be operated only under the supervision of the holder of an appropriate class of operator's license; thus, if a licensed operator is not already a member of the testing staff, a staff member should obtain such an operator's license.

C.3.2 Selecting frequencies

A table of frequency allocations from the appropriate regulatory agency should be studied to select frequencies that are most likely to be approved. In general, frequencies will probably be approved where no interference to other licensed radio services is likely to occur. The length of time each frequency will be used should always be stated. If frequencies are to be used intermittently, that is, for periods of only a few minutes at a time only a few times per hour, they are more likely to be approved. Under intermittent use, interference tends to be minimized, and the regulatory agency may approve intermittent use of frequencies for which continuous use could not be approved. It is advisable to keep the request in the business, industrial, and petroleum radio-service frequencies. Frequencies to avoid include the following:

a) In general, the domestic public radio service frequencies should be avoided, since this service is protected. Police and fire frequencies should also be avoided.

b) The exact frequency of a commercial broadcast station should be avoided if there is a reasonable chance that interference will occur.

c) The following frequencies should not be requested: on or within the guard bands, or any emergency frequencies in any of the VLF, LF, MF, or HF radio navigation channels that may be active at or near the test locations.

d) Government frequencies should be avoided. If government frequencies are needed, the local area frequency coordinator should be contacted through the nearest military base communications officer. Early establishment of rapport with the area frequency coordinator is beneficial in any situation. If the coordinator is satisfied that there will be no harmful interference to the government radio services for which he or she is responsible, he or she will likely help obtain license authorization for government frequencies.

e) Standards frequencies, such as those used by WWV, CHU, U.S. Naval Observatory, and other international time and frequency stations, should be avoided. Radio-astronomy frequencies that are active in or near the test area should also be avoided.

All requests should be for discrete frequencies. A request for a band of frequencies should include a justification of why discrete frequencies cannot be used.

C.3.3 Suggested measurement frequencies

Suggested frequencies for susceptibility test use are shown in two lists. The first list (Table C.1) consists of authorized frequencies (within the United States) for Instrument, Scientific, and Medical (ISM) and field disturbance sensors (FDS).

Table C.1—United States ISM and FDS frequencies

kHz	MHz
6780 ± 15	915 ±13
13 560 ± 7	2450 ± 50
27 120 ± 163	5800 ± 75
40 680 ± 20	24 125 ± 125

The test frequencies of Table C.2 are spaced unevenly throughout the spectrum to avoid conflict with known unapprovable frequencies. Some of these suggested frequencies may not receive approval in all countries.

Table C.2—Suggested test frequencies for the 9 kHz to 18 GHz range

kHz	kHz	MHz	MHz	MHz	GHz
10	111	1.0[12]	13.56	130	1.29[13]
14.0	130	1.3[12]	16.00	160	1.86
16.0	160	1.995	20.02	209	2.1[13]
20.5	200	2.6	27.12	260[14]	2.45
25	250	3.2	33.30	327[14]	3.29
32	326	4.06	40.68	415[14]	4.19
40	400	5.1	52	523[12]	5.80
50	520	6.525	65[12]	661[12]	6.6
64	640[12]	8.1	81[12]	830	8.4[13]
80	810[12]	10.1	100[12]	915	10.495[13]
					13.22
					18

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[12] These frequencies are in the broadcasting bands. Check to see if the listed frequencies are occupied, and if so, select a nearby locally non-allocated frequency.

[13] In some cases, these are shared government/non-government frequencies; thus, some problem in assignment of these frequencies may occur.

[14] These frequencies may be part of a government band, and therefore might not be assignable or authorizable. The local area frequency coordinator (or equivalent authority) may be able to assist in selecting frequencies.

Annex D

(informative)

Guidelines for the selection of measurement techniques (for Part I – 0.75 m to 2 m enclosures)

D.1 Types of enclosures

Shielded enclosures may be categorized generally by three criteria:

a) Method of construction
b) Shielding material
c) Intended application

Method of construction refers to such factors as, but is not limited to, single shield, double shield (cell), double electrically isolated (DEI) shield, bolted modular, fixed location or demountable configuration, and welded techniques. The shielding material may consist of, but not be limited to, copper (solid or screen), steel (sheet or plate), aluminum, and a variety of metalized fabrics or similar substrates. Applications may include, but not be limited to, anechoic chambers for military specification compliance testing, semi-anechoic chambers for commercial EMC compliance testing, mode-stirred chambers, experimental applications for research and development, commercial production or repair facility for RF equipment, medical imaging and treatment facilities, and scientific experimental facilities.

The correct and cost-effective application of this standard requires that the above criteria be considered when selecting which test procedures and which test frequencies will be used for any given shielded enclosure requirement. In some cases, special techniques, such as frequency sweeping, may be required. Refer to other annexes for details. Some application examples are as follows:

d) A welded steel enclosure to be used for military application would most likely be specified for testing in each of the frequency ranges and have a high level of shielding effectiveness (nominally greater than 100 dB).
e) A single copper shield, bolted together in panel sections and intended for medical MRI applications, would most likely be tested only in the resonant range and be required to have a shielding effectiveness in the range of 80 dB to 100 dB.
f) A steel cell structure to be used for test and repair of VHF and UHF radio equipment would most likely be tested only in the high range.
g) A portable, collapsible test cell for field applications and made of metalized fabric or screening would most likely require a low performance level in the resonant and/or high ranges.

D.2 Performance requirements

Shielded enclosures are generally specified with some shielding performance requirement at the time they are designed, ordered, or built. The purpose of this standard is to provide a uniform test method for all enclosures meeting the criteria of 1.2. The selection and application of methods described herein is the responsibility of the parties associated with the enclosure: principally the owner and the owner's representatives. It would not be possible to fully test in accordance with this standard if the standard requires procedures or techniques that are inappropriate or incompatible with the particular enclosure involved.

D.3 Equipment requirements

It is the intent of this standard that test equipment used to measure shielding performance be appropriate for the application. The individual clauses for each of the techniques and frequency ranges determine the general equipment and antenna probes needed. It is the responsibility of the associated parties to ensure that adequate frequency and dynamic range are available. This standard requires that the measurement system have a usable dynamic range that is no less than 6 dB greater than the specified or expected shielding performance of the enclosure. Stated another way, there should be enough dynamic range such that any data collected would be 6 dB above the noise floor. Available technology will vary over the applicable frequency range of this standard, and it is expected that judicious use of RF power amplifiers and preamplifiers will be made as needed.

D.4 Regulatory agency conflicts

Due to regulatory limits on transmitting in some frequency bands, outside-in tests (with transmit antenna on the outside and receive antenna on the inside) may be prohibited. In this case, inside-out testing (with transmit antenna on the inside and receive antenna on the outside) may be required; however, the following issues need to be considered:

a) The Reference Field test procedures are done in the existing manner, but shall be done quickly because open transmitting is required.

b) Once the chamber door is closed, cavity effects on the "net" reference level need to be considered. This is especially important for test frequencies near and above the fundamental resonant frequency of the chamber.

c) Revision/change of the test placement figures is required to correctly depict this test arrangement. Test placement figures depicting the actual test arrangement should be included in the test report. Test personnel who shall employ inside-out testing should carefully study the existing test point location figures and modify them accordingly. All test locations should be noted in the test documentation.

d) Accessibility to floors and other surfaces that may be partially or fully blocked will limit the extent to which leakage points may be determined.

e) Measure and record the outside ambient signal level at all proposed test frequencies prior to start of testing.

Use of the inside-out technique may significantly limit the selection of test frequencies due to high ambient noise levels.

Annex E

(informative)

Preliminary measurements and repairs (for Part I – 0.75 m to 2 m enclosures)

It may be that the shield requires minor, and possibly major, repairs before the SE measurements are made. For reasons of efficiency, it is recommended that the shield receive a cursory check before the final SE measurements are made in accordance with 7.1. This annex contains a recommendation for procedures to perform this check. A cursory check is not required by the standard, however.

E.1 Background

Preliminary check procedures, while not mandatory, are provided as a standardized reference whenever it is decided that performing a preliminary scan may be beneficial, particularly in identifying areas of significant leakage prior to taking formal SE data.

E.2 Frequencies for preliminary check

These are the procedures for the normal range of frequencies, and they may also be applied to the extended range.

For the low range of frequencies (9 kHz to 20 MHz), small magnetic loops (typically less than 1 m in diameter) are useful as source and sensor antennas; in the resonance range (20 MHz to 300 MHz), biconical and electric dipoles are recommended; and in the high range (300 MHz to 18 GHz) dipoles, horns, or equivalent antennas can be used.

To provide a means for measuring performance of enclosures, single-frequency measurements should be made in accordance with the test plan (see 4.2) using any of eight fairly narrow bands as required: 9 kHz to 16 kHz, 140 kHz to 160 kHz, 14 MHz to 16 MHz, 50 MHz to 100 MHz, 300 MHz to 400 MHz, 600 MHz to 1000 MHz, 8.5 GHz to 10.5 GHz, and 16 GHz to 18 GHz. (Test frequencies unique to the specific installation should also be considered.)

WARNING

For all measurements undertaken as a part of this standard, care shall be taken to protect personnel from potentially hazardous RF field levels (IEEE Std C95.1-2005). This standard also suggests that authorization for transmit operation be obtained from the appropriate regulatory agency prior to activation of any transmitter. See C.2. Care shall also be taken to avoid interference with other electronic equipment operating in the vicinity.

E.3 Preliminary check procedures

Prior to making any preliminary scan or measurement, the signal measuring device shall be tested for signal penetration of its case. Ancillary equipment (such as blowers and fans) normally present during operation of the enclosure shall remain in place during the test. Other equipment that is not a normal part of the enclosure shall be removed prior to test.

The transmitting and receiving antennas should be positioned roughly as shown for the various tests in 7.1 (see Figure 2, Figure 3, Figure 4, Figure 7, and Figure 8); however, for the preliminary check it is recommended that the antennas be located and oriented to produce the largest response possible. A scan should be made along all accessible shielding faces to detect areas of poor performance prior to actual measurement. Items that should be checked are doors, power-line filters, air vents, seams, coaxial cable and waveguide fittings, emergency egress panels for personnel, and fluid piping penetration points.

Based on the results of these measurements and the sizes of the observed leaks, the owner and testing organization can then decide whether to proceed with full SE testing or have repairs made before full SE testing.

Annex F

(informative)

Rationale for wall-mounted monopoles

This annex discusses the rationale of using a wall-mounted monopole, and shows that power in an enclosure can be measured either in the center of the enclosure or at the wall of an enclosure. At sufficient distances from the walls, stirrer(s), and source(s) in a reverberation chamber, the ensemble average (over stirrer position or frequency) of the squared magnitude of the electric field is independent of position. This property of statistical uniformity and other field properties can be derived from a plane wave integral representation with random coefficients of appropriate statistical properties [B11]. Statistical uniformity has been verified experimentally with an array of field probes [B6], [B21]. The mean-square electric field is denoted as E_0^2. In this environment, the average power received by an antenna is independent of position and orientation and can be written as Equation (F.1) [B11]:

$$< P_r >= \frac{1}{2}\frac{E_0^2}{\eta}\frac{\lambda^2}{4\pi} \tag{F.1}$$

where η is the free-space impedance and λ is the free-space wavelength. The physical interpretation of Equation (F.1) is that the average received power is the product of the average scalar power density E_0^2 / η times the effective area $\lambda^2 / 4\pi$ of an isotropic antenna times a polarization mismatch factor of 1/2 [B24]. When necessary, antenna efficiency and impedance mismatch [B11], [B26] can also be included in the equation. Equation (F.1) and the following analysis applies to either the reverberation chamber or the shielded enclosure, which shall also be electrically large. In the reverberation chamber the source is a transmitting antenna, and in the shielded enclosure the source is leakage. However, the source does not affect the analysis because we are dealing with stirred fields.

F.1.1 Field behavior near a wall

Before proceeding to received power, it is instructive to analyze the fields that will illuminate the receiving antenna. Fields in rectangular reverberation chambers have been analyzed for locations near a single wall (planar interface), two walls (right angle bend), or three walls (right angle corner) [B14]. For practical applications with a monopole probe penetrating a chamber wall, the normal electric field far from the other chamber walls is of most interest. Following the derivation in [B14] and [B11], it can be shown that the well-stirred field component far from chamber walls (i.e., center of chamber) is given by Equation (F.2):

$$\left\langle | E_y^t(x,y,z) |^2 \right\rangle_{center} = \frac{E_0^2}{3} \tag{F.2}$$

At the wall boundary ($y = 0$), we have Equation (F.3):

$$\left\langle | E_y^t(x,0,z) |^2 \right\rangle = \frac{2E_0^2}{3} \tag{F.3}$$

Thus, the mean-square value of the normal component of the electric field is twice that of the value far from the chamber wall. These two quantities can be used to determine the power received by either a dipole in the center of a chamber or a monopole mounted to the wall of a chamber.

F.1.2 Received power by dipole and monopole antennas

The purpose of this annex is to show that a dipole in the center of the chamber (see Figure F.1) and a wall-mounted monopole (see Figure F.2) receive the same power. The case of a linear dipole antenna has been treated in [B14] and [B10], and we will summarize the results here. The sinusoidal approximation for the current $I(y)$ when the transmitting dipole is oriented in the y direction and centered at $y = y_c$ is given by Equation (F.4) [B19]:

$$I(y) = I_0 \frac{\sin k(H - | y - y_c |)}{\sin kH} \tag{F.4}$$

where I_0 is the current at the center of the dipole, and H is the half length of the dipole. Equation (F.4) is an adequate approximation for $H < \lambda / 2$. When the dipole is receiving, the open-circuit voltage V_{oc} can be determined by the induced EMF method given by Equation (F.5) [B19]:

$$V_{oc} = -\frac{1}{I_0} \int_{y_c - H}^{y_c + H} E_y^i(y') I(y') \, \mathrm{d}y' \tag{F.5}$$

Because one assumes that the dipole is far from chamber walls, the incident field E_y^i takes the plane-wave integral form over 4π steradians [B10] rather than 2π steradians as is the case for a wall-mounted monopole.

When the dipole is terminated with a matched load, $Z_L = Z_d^*$, where Z_d is the dipole impedance, the average value of the received power can be written as Equation (F.6):

$$\langle P_r \rangle = \frac{<| V_{oc} |^2>}{4R_d} \tag{F.6}$$

where $R_d = \mathbf{Re}(Z_d)$ is the input resistance of the dipole. The average of the square of the open-circuit voltage can be derived from Equation (F.5) given as Equation (F.7):

$$<| V_{oc} |^2> = \frac{1}{I_0^2} \int_{y_c - H}^{y_c + H} \int_{y_c - H}^{y_c + H} \left\langle E_y^i(y_1) E_y^{i*}(y_2) \right\rangle I(y_1) I(y_2) \, \mathrm{d}y_1 \tag{F.7}$$

By using Equation (F.4) and the expression for the field component given in [B14], [B11], and [B8], this integral can be evaluated and once substituted into Equation (F.6), the power received by a dipole in the center of a chamber is given by Equation (F.8):

$$< P_r >_{dipole} = \frac{1}{2} \frac{E_0^2}{\eta} \frac{\lambda^2}{4\pi} \tag{F.8}$$

which is identical to that given in Equation (F.1). This is the expected result, since Equation (F.1) is valid for general antennas, but it is useful to derive the result for a linear dipole by the induced EMF method because it sets the stage for analysis of the related case of a wall-mounted monopole antenna.

Now consider a y-directed monopole of length H fed at the planar wall ($y = 0$). When the monopole is transmitting, the sinusoidal current approximation is the same as that for the isolated dipole in Equation (F.4) except that $y_c = 0$ and the current exists only for positive y given by Equation (F.9):

$$I(y) = I_0 \frac{\sin k(H-y)}{\sin kH}, \; 0 < y < H \tag{F.9}$$

In a manner similar to Equation (F.5), we can write the open circuit voltage using the induced EMF method [B19] given by Equation (F.10):

$$V_{oc} = -\frac{1}{I_0} \int_0^H E_y^t(y') I(y') \, \mathrm{d}y' \tag{F.10}$$

The total electric field E_y^t in Equation (F.10) can be written as the sum of the incident field and its image [B8] given by Equation (F.11):

$$E_y^t(y') = E_y^i(y') + E_y^i(-y') \tag{F.11}$$

When the monopole is terminated with a matched load, $Z_L = Z_m^*$, where Z_m is the monopole impedance, the average value of the received power can be written as Equation (F.12):

$$\left\langle P_r \right\rangle = \frac{<|V_{oc}|^2>}{4R_m} = \frac{<|V_{oc}|^2>}{2R_d} \tag{F.12}$$

The right-hand expression in this equation results from the fact that the monopole impedance and resistance equal one half that of a dipole antenna of length 2H [B19] given by Equation (F.13):

$$Z_m = Z_d / 2 \quad \text{and} \quad R_m = R_d / 2 \tag{F.13}$$

The average of the square of the open-circuit voltage can be derived from Equation (F10) can be given by Equation (F.14):

$$<|V_{oc}|^2> = \frac{1}{I_0^2} \int_0^H \int_0^H \left\langle E_y^t(y_1) E_y^{t*}(y_2) \right\rangle I(y_1) I(y_2) \, \mathrm{d}y_1 \, \mathrm{d}y_2 \tag{F.14}$$

By using Equation (F.9) and the expressions for the field component given in [B14], [B11], and [B8], this integral can be evaluated and once substituted into Equation (F.12), the power received by a monopole mounted on a wall of a chamber is given by (details of which are given in the IEC 61000-5-7) Equation (F.15):

$$< P_r >_{monopole} = \frac{1}{2} \frac{E_0^2}{\eta} \frac{\lambda^2}{4\pi} \tag{F.15}$$

This is the same result for the isolated dipole (or any other isolated, matched antenna) as given in Equation (F.1) and Equation (F.8). The result in Equation (F.15) is important because it shows that a wall-mounted monopole can be used to monitor the field strength in the center of the chamber. Hence, the receiving antenna configurations of either an antenna placed in the center of the chamber or a monopole mounted to the chamber wall are equivalent for monitoring the chamber field strength. For a physically small chamber, the wall-mounted monopole could be advantageous.

In [B14] the case of an electrically short monopole ($kH << 1$) was analyzed and it was shown that the average received power is given by Equation (F.16):

$$< P_r >= \frac{E_0^2}{\eta} \frac{\lambda^2}{8\pi} \tag{F.16}$$

A similar analysis has been performed for a short dipole antenna in [B11] and gives the same results. Hence, the receiving antenna configurations of either a short dipole placed in the center of the chamber or a short monopole mounted to the chamber wall are equivalent for monitoring the chamber field strength. A dipole receiving antenna in the center of a reverberation chamber is shown in Figure F.1. A monopole receiving antenna mounted on the wall of a reverberation chamber is shown in Figure F.2.

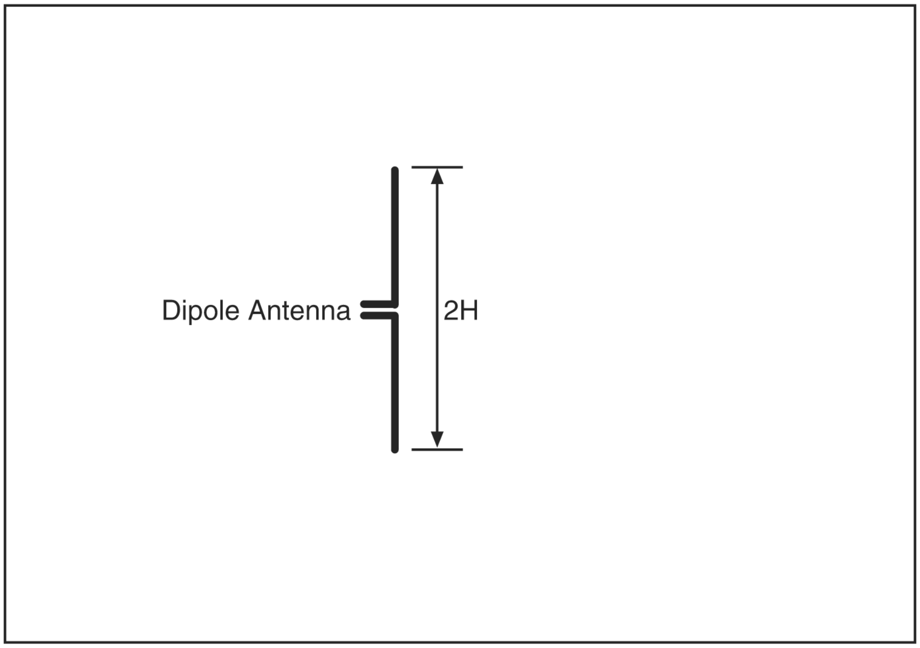

Figure F.1—Dipole receiving antenna in the center of a reverberation chamber

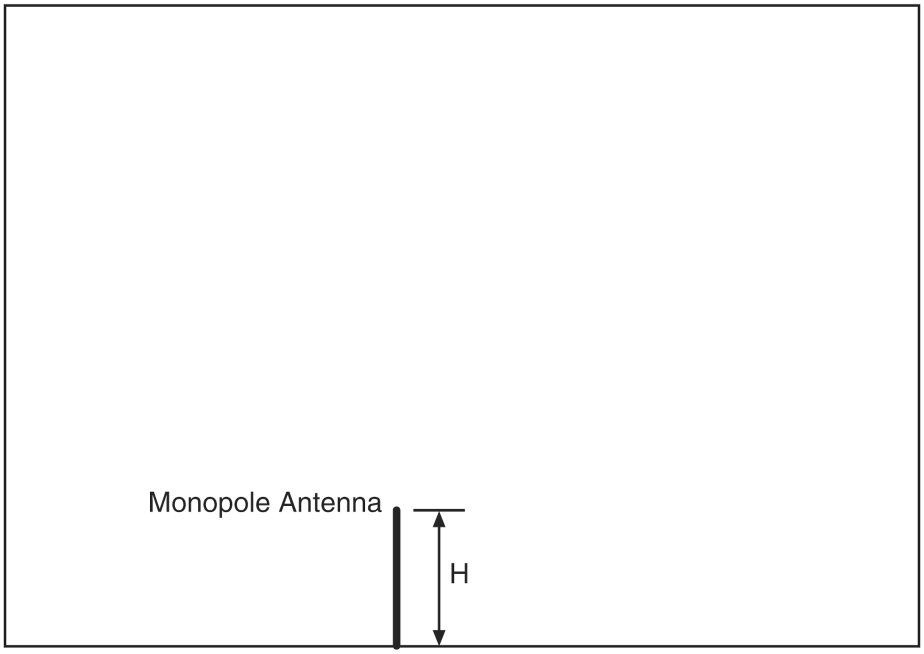

Figure F.2—Monopole receiving antenna mounted on the wall of a reverberation chamber

Annex G

(informative)

Impedance mismatch correction

In this annex, the rational for the mismatch correction discussed in 7.2.2 is discussed in detail. When using small monopole antennas, one has to be careful with the issue of antenna impedance mismatch. In typical reverberation chamber applications, individuals use antennas that are well matched over the frequency range of interest. However, if small monopole antennas are used, large reflections at the antenna terminal can occur due to the poor impedance match of the small monopole antenna to the transmission line used to deliver power to the antenna terminal. In order to obtain consistent results, the reflections due to mismatch shall be corrected. The correction is explained by noting that the mismatches associated with the monopole (the antenna on the wall of the small enclosure) will result in measurements of $\left\langle |S_{31}|^2 \right\rangle$ being appreciably lower than measurements of $\left\langle |S_{31}|^2 \right\rangle$ when a well matched antenna is used at Port 3 (see Figure G.1). Equivalently, given the same power transmitted through the antenna on Port 1, the power received by the monopole at Port 3 will be less than the power coupled to a well matched receiving antenna at Port 3. To correct for this, one applies a mismatch correction to estimate the power that would have coupled to the monopole had it been well matched. If the coupling C_{31} to the monopole is $\left\langle |S_{31}|^2 \right\rangle$, then the corrected coupling $\widetilde{C}_{31}$ is given as Equation (G.1):

$$\widetilde{C}_{31} = \frac{\left\langle |S_{31}|^2 \right\rangle}{1 - |S_{33}|^2} \tag{G.1}$$

where S_{33} is the free-space reflection coefficient of the monopole. We estimated $|S_{33}|^2$ from our reverberation chamber measurements of $\left|\left\langle S_{33} \right\rangle\right|^2$.

The effect of not using this correction is shown in Figure G.2, which shows $|S_{31}|$ obtained with and without the correction. The data without the correction shows an oscillation as a function of frequency. This oscillation is associated with the classical resonances seen in the input impedance of linear antennas.

Similarly, if the antenna at Port 2 (the antenna used to monitor the power outside the small enclosure, see Figure G.1) is not well matched, large reflections can occur. Once again, in order to obtain consistent results, the reflections due to mismatch shall be corrected as well. The correction is explained by noting that the mismatches associated with the poor antenna at Port 2 will result in measurements of $\left\langle |S_{21}|^2 \right\rangle$ being appreciably lower than measurements of $\left\langle |S_{21}|^2 \right\rangle$ when a well matched antenna is used at Port 2. Equivalently, given the same power transmitted through the antenna on Port 1, the power received at Antenna Port 2 will be less than the power when a well matched antenna is used at Port 2. To correct for this, one applies a mismatch correction to estimate the power that would have coupled to the antenna at Port 2 had the antenna at Port 2 been well matched. If the coupling C_{21} to the antenna at Port 2 is $\left\langle |S_{21}|^2 \right\rangle$, then the corrected coupling $\widetilde{C}_{21}$ is given as Equation (G.2):

$$\tilde{C}_{21} = \frac{\left\langle \left| S_{21} \right|^2 \right\rangle}{1 - \left| S_{22} \right|^2} \tag{G.2}$$

where S_{22} is the free-space reflection coefficient of the monopole. We estimate $\left| S_{22} \right|^2$ from our reverberation chamber measurements of $\left| \left\langle S_{22} \right\rangle \right|^2$.

Taking both of these mismatch effects into account, the SE for the small enclosure can be written as Equation (G.3):

$$SE = \frac{\tilde{C}_{31}}{\tilde{C}_{21}} \tag{G.3}$$

and using Equation (G.1) and Equation (G.2), the SE is expressed as Equation (G.4):

$$SE = \frac{\left\langle \left| S_{31} \right|^2 \right\rangle}{\left\langle \left| S_{21} \right|^2 \right\rangle} \frac{1 - \left| \left\langle S_{22} \right\rangle \right|^2}{1 - \left| \left\langle S_{33} \right\rangle \right|^2} \tag{G.4}$$

The second term in Equation (G.4) is required to correct antenna mismatch issues. This correction term approaches one (1) for well matched antennas. Note when the correction due to S_{33} is not used, an underestimate of SE results. On the other hand, when the correction due to S_{22} is not used, an overestimate of SE results. The use of small monopole antennas in the small enclosure requires the denominator in this correction term. However, since one typically uses well matched antenna in the outer reverberation chamber, the numerator is approximately one (1).

The antenna at Port 1 (the source antenna in the outer reverberation chamber, see Figure G.1) could also not be well matched. If so, one could add a correction term involving $\left| S_{11} \right|^2$ in both Equation (G.1) and Equation (G.2). However, since the SE is the ratio of $\tilde{C}_{31}$ and $\tilde{C}_{21}$ as defined in Equation (G.3), the correction for the mismatch for the antenna at Port 1 is not required because it would cancel. With this said, it is good practice and highly recommended that a well matched antenna (for the frequency range of interest) be used as the source antenna (Port 1) for the outer reverberation chamber.

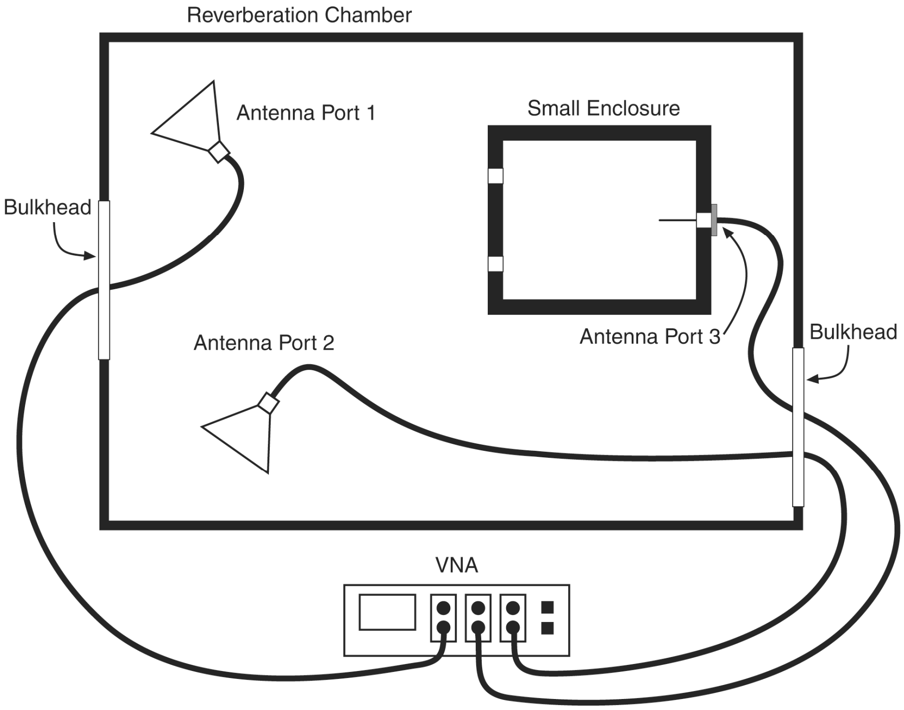

Figure G.1—Antenna configurations for measuring shielding effectiveness

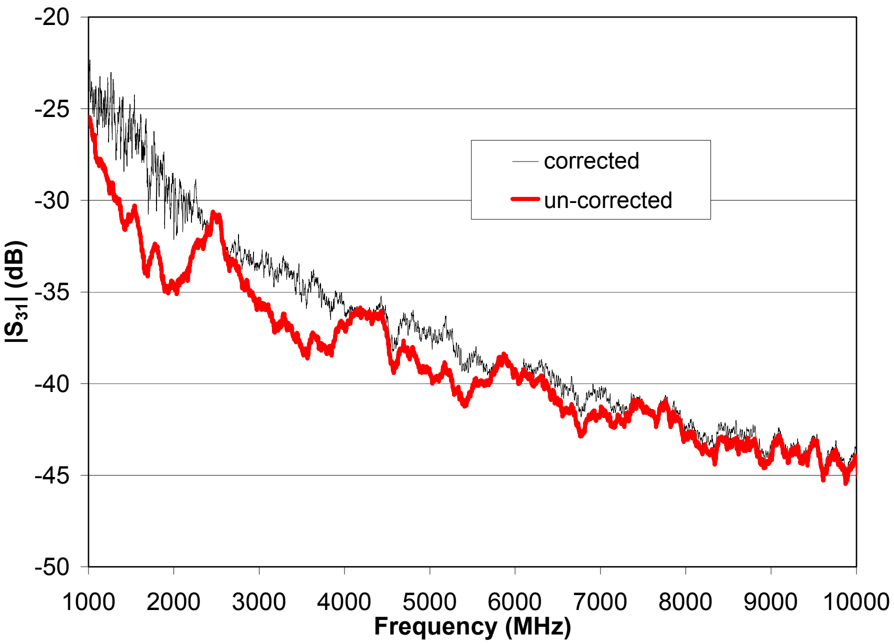

Figure G.2—Comparison of $|S_{31}|$ obtained for the monopole antenna with and without the mismatch correction

Annex H

(informative)

Using isolated monopoles in outer reverberation chamber

As stated in 7.2.2, 7.2.6, and [B14], any antenna could be used to monitor the power outside the small enclosure. However, if one attempts to use an isolated monopole (for example, the extended center conductor of a coaxial cable, see Figure H.1), the effectiveness is less clear because it is hard to determine where the antenna starts and the feedline ends. (Currents typically are induced on the shield of the coaxial cable.) If a ground plane is included (as in Figure H.2), then the feed cable is shielded and the antenna performance is essentially equivalent to any efficient, well matched antenna. These effects were studied in feeding a microstrip transmission line radiator [B12].

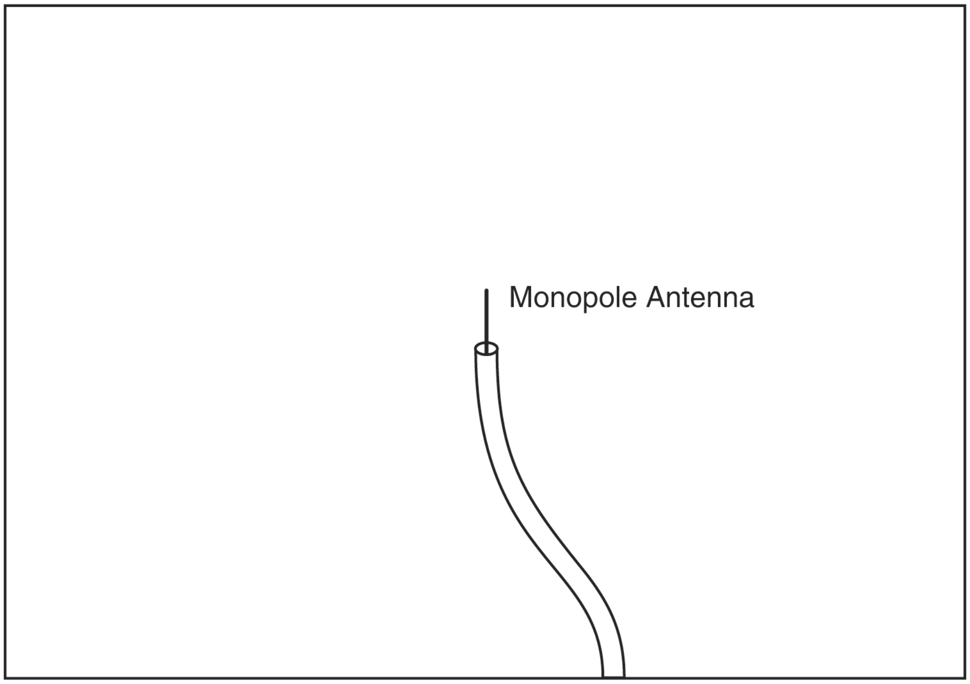

Figure H.1—Monopole antenna in a reverberation chamber without a ground plane

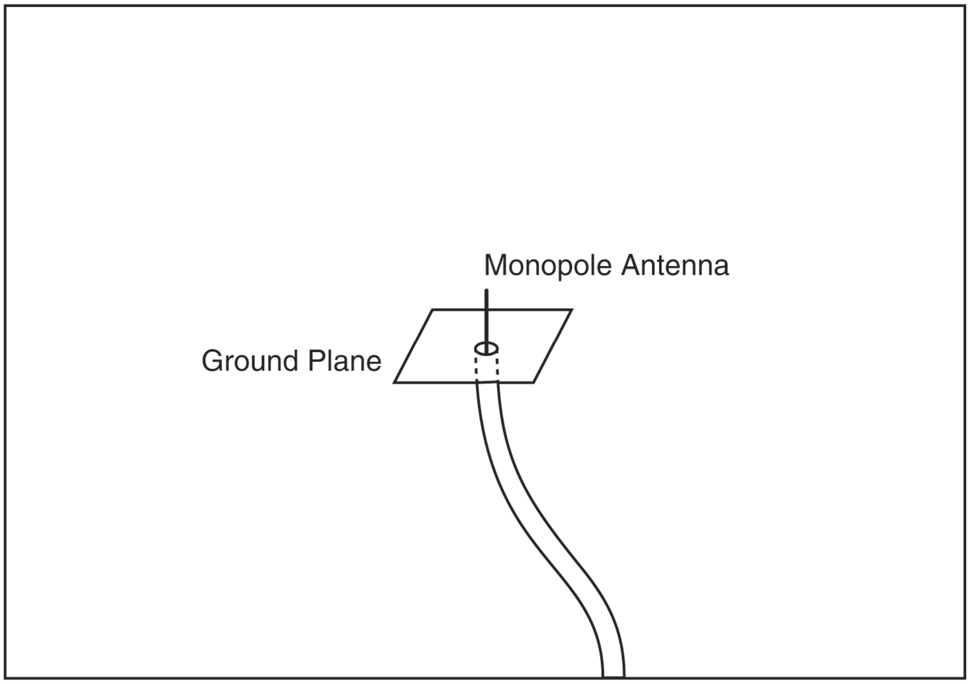

Figure H.2—Monopole antenna in a reverberation chamber with a ground plane

Annex I

(informative)

Measuring the shielding effectiveness of physically small and electrically small enclosures using magnetic field measurements (≤ 300 MHz)

I.1 Purpose

The purpose of this annex is to characterize the electromagnetic shielding of small enclosures over the frequency range in which they are electrically small. For the purposes of this annex, the small enclosures have dimensions that are in the range of 0.1 m to 0.75 m. Being electrically small means that the upper frequency for credible measurements shall be such that the wavelength shall be large compared to the largest dimension of the enclosure. Alternatively, the largest dimension of the enclosure shall be small compared to the wavelength. This requirement is satisfied if the following conditions of Equation (I.1) are met:

$$\ell < \frac{\lambda}{10} \tag{I.1}$$

where ℓ is the largest dimension of the enclosure, and λ is the shortest wavelength that can be used for valid measurements.

This is considerably smaller than the wavelength of the first resonance. These criteria can be converted to upper bound frequencies using Equation (I.2), since:

$$f = \frac{c}{\lambda} \text{ or } \lambda = c/f \tag{I.2}$$

where c is the velocity of light (3×10^8 m/s in air), this condition is equivalent to that defined in Equation (I.3):

$$f < \frac{c}{10\ell} \tag{I.3}$$

This also means that the upper frequency, f, shall be less than 300 MHz, depending on the criteria for an enclosure whose longest interior dimension is shorter than 0.1 m and less than 40 MHz for an enclosure whose longest dimension is shorter than 0.75 m. Note that these upper bound frequencies are considerably less than the half wavelength cavity resonance frequencies (1.5 GHz and 200 MHz respectively). Additional constraints on the upper frequency limit are imposed by the size and design of the test fixture and sensors.

This annex only measures the magnetic field shielding effectiveness for the principal component, namely the component that is normal to the current flow. The non-principal components are assumed to be smaller. If other orientations are desired, the enclosure may be reoriented in the test fixture.

Although many standards seek to measure the magnetic and electric field shielding, this annex only measures the magnetic field shielding effectiveness. This is sometimes called the surface magnetic field attenuation. The assumption is made that the electrically small enclosure is made of conductive material having a surface resistance of less than a few ohms. Under these conditions, an electric field cannot exist because it is shorted out by the enclosure walls.

I.2 Rationale

The test methodology requires that the enclosure under test be placed in a terminated strip line or TEM cell, preferably 50 Ω, driven by the output of a vector network analyzer, and, if necessary, a power amplifier. This test fixture produces both electric and magnetic fields. Only the magnetic field will be measured. The magnetic field on the surface of the strip line electrodes and inside the enclosure is measured using small identical loops. The output of the two sensors is measured by two channels of the vector network analyzer. The ratio of the output of the sensor on the strip line electrode to the output of the sensor inside of the enclosure is the Magnetic Field Shielding Effectiveness or Surface Magnetic Field Attenuation.

Some vector network analyzers measure S-param and do not have two measurement channels. These network analyzers can be used to measure the shielding effectiveness of enclosures by making two measurements, one for the sensor measuring the magnetic field in the strip line and one for measuring the magnetic field in the enclosure. The measurements are stored in a computer, which then computes their ratio.

I.3 Test setup and circuits

I.3.1 Strip line

Figure I.1 shows the test setup and strip line details. The strip line is simple version of a TEM cell or terminated parallel plate transmission line. The output of the network analyzer feeds input port of the test fixture. The other end of the transmission line is terminated by a combination of resistors equally spaced with a combined parallel impedance value of 50 Ω. For the highest upper bound frequency, the test fixture should be terminated in its characteristic impedance. If high frequencies are not as important, the termination can be 50 Ω, and the test is simplified. Although not absolutely necessary, a voltage measuring port at the termination is often useful for troubleshooting and diagnostic measurements. A 500 Ω to 5,000 Ω resistor between the termination and the port isolates this measurement location from the normal measurement ports.

The length of the transmission line is normally the longest dimension of the test fixture. The lowest resonant frequency occurs when the length of the transmission line is a half wavelength long. For this frequency to be greater than 200 MHz, the transmission line shall be less than 0.75 m.

The strip line dimensions should be at least three times the dimensional values of the sample under test to ensure a reasonably uniform field surrounds the sample.

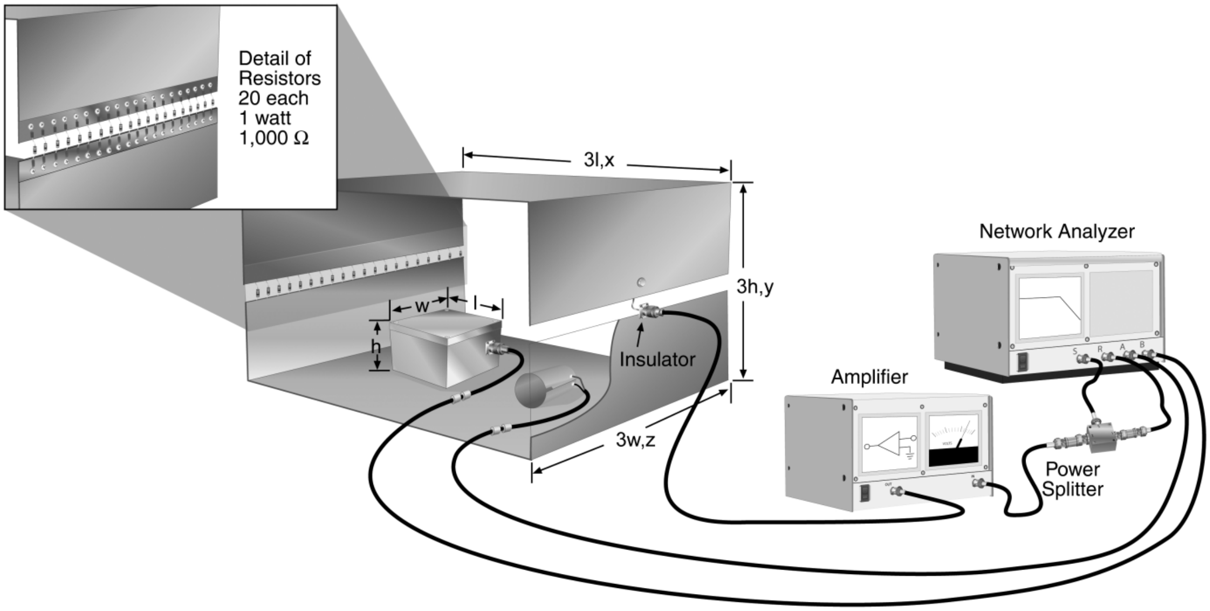

Figure I.1—Strip-line test setup for magnetic field-based test

The electric field strength in volts per meter (V/m) at the center of the fixture is equal to the applied voltage divided by distance (*d*) between the plates and is given by Equation (I.4):

$$Electric\ Field\ Strength\,(\mathrm{V/m}) = \frac{V}{d} \tag{I.4}$$

The magnet field H (A/m) on the surface of the plates and the test object is given by Equation (I.5):

$$H\ (A/m) = E / 120\pi = V / 120\pi\, d \tag{I.5}$$

A reasonably built strip line should maintain a field uniformity within ± 2 dB within the test area. With no test sample within the volume, the field strength should be measured at 16 evenly distributed points within the test area. The field homogeneity should not exceed 6 dB. To verify the homogeneity of the field strength, the mean value and the standard deviation for the $n = 16$ samples shall be calculated. The homogeneity of the field is given by Equation (I.6):

$$Field\ Homogeneity\,(dB) = 20\log\frac{\overline{x} + (1.15 \times s)}{\overline{x} - (1.15 \times s)} \tag{I.6}$$

I.3.1.1 Sensor probes

The loop sensors are constructed from copper foil strips (tape) applied to a plastic foam cube, cylinder, or other shape whose dimensions allow adequate spacing within the sample under test (refer to Figure I.2).

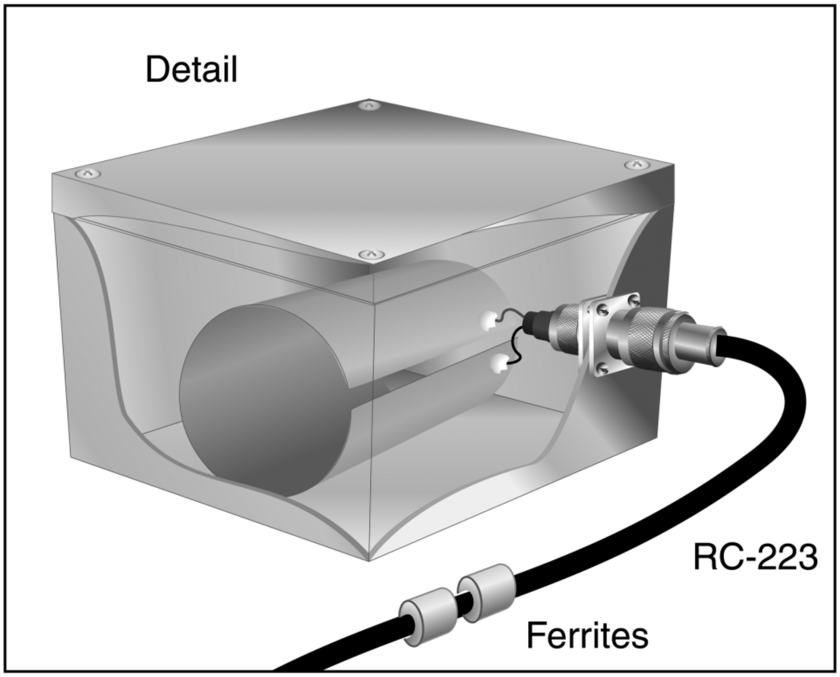

Figure I.2—Loop sensor detail

Small loops are ideal for this type of measurements where space is limited. The relationship between flux density and the resulting voltage produced is represented by the Thévenin equivalent circuit in Figure I.3.

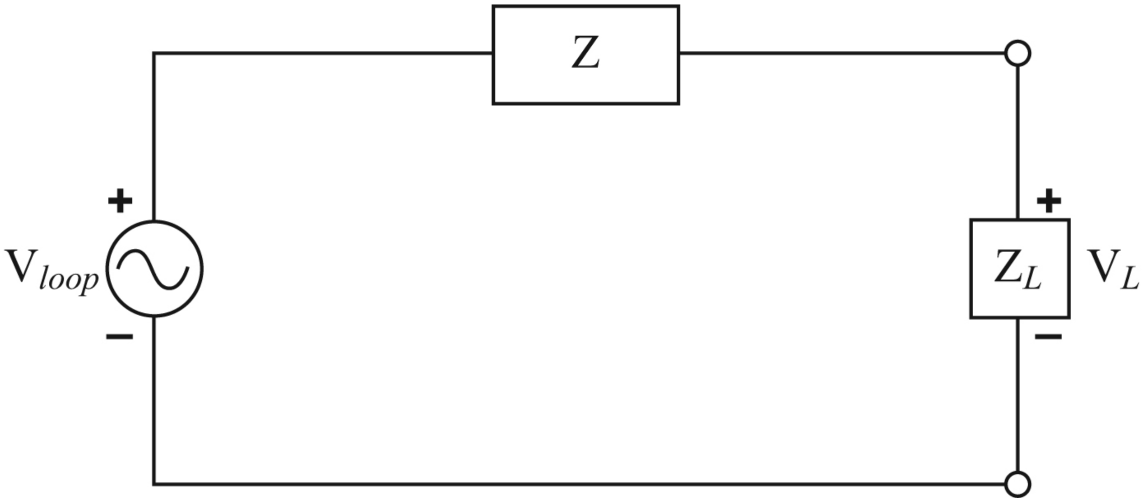

Figure I.3—Thévenin equivalent circuit

The voltage developed across the output of the loop is equal to the time rate of change of the magnetic flux, Φ, through the loop. The loop voltage is given by Equation (I.7):

$$V_{loop}(t) = - d\Phi / dt = - d\,(B\,A)\,dt \tag{I.7}$$

In the frequency domain, this becomes Equation (I.8):

$$V_{loop}(\omega) = -j\omega BA \tag{I.8}$$

This voltage is divided between the impedance of the loop (primarily an inductance, L_{loop}) and the input impedance (R_{in}) of the measurement instrument (generally 50 Ω). Thus, the voltage, $V_R(\omega)$, at the input of the measurement instrument is given by Equation (I.9):

$$V_R\,(\omega) = (R_{in}/(R_{in} + j\omega L_{loop}))\;(-j\omega BA) = j\omega BA/(1 + (j\omega L_{loop}/R_{in}) \tag{I.9}$$

In order to understand the frequency characteristics of the loop sensors, it is convenient to define a break frequency, ω_o, as the frequency where the ratio of the measurement instrument's input resistance, R_{in}, to the loop inductance, L_{loop}, is equal to unity (1). The break frequency is given by Equation (I.10):

$$\omega_o = R_{in}/L_{loop} \tag{I.10}$$

Then, the expression for $V_R(\omega)$ can be written as Equation (I.11):

$$V_R\,(\omega) = -j\omega BA/(1 + (j\omega/\omega_o)) \tag{I.11}$$

At low frequencies, where $\omega << \omega_o$, $V_R(\omega)$ is given by Equation (I.12):

$$V_R\,(\omega) = -j\omega BA \tag{I.12}$$

In this frequency range, the sensor is a B-dot loop.

At high frequencies, where $\omega >> \omega_o$, $V_R(\omega)$ is given by Equation (I.13):

$$V_R\,(\omega) = -j\omega BA/j\omega/\omega_o = -\,BA\omega_o = -\,BAR_{in}/L_{loop} \tag{I.13}$$

In this frequency range, the sensor is said to be "self integrating" and the input to the measuring instrument is frequency independent.

The inductance of a loop of width *W* and cross-section *A* is given by Equation (I.14):

$$L_{loop} = \mu_o\,A/W \tag{I.14}$$

Thus, the inductance of a loop made from a cube of foam, 5 cm on a side, would be 63 nH.

The break frequency for the 5 cm cube sensor and a 50 Ω measuring instrument is an angular frequency of 794×10^6 radians/s or 126 MHz.

Sensitivity can be traded for bandwidth. Shunting the sensor at the loop will reduce the break frequency, thus extending the "Self Integrating" effect to lower frequencies at the expense of reducing the sensitivity. To increase the break frequency and thus extend the B-dot region to higher frequencies, a resistance shall be inserted in the circuit (which will reduce the sensitivity) or the inductance shall be reduced by making the loop wider and/or smaller.

Note, that by using identical sensors, the individual frequency responses of the sensors cancel when the vector network analyzer calculates the ratio of the outputs of sensors outside and inside the enclosure under test.

I.3.1.2 Ferrite loading of cables

Ferrite loading may be required to null any parasitic pickup effects from the coaxial cables; typically, the loading works best at the sensor end of the cable and or close to the measurement instrument. A variety of double-shielded coaxial cable (RG-232, RG-55) and ferrite screened cables are available, which may reduce the need for additional discrete ferrite loading.

I.3.1.3 Test equipment noise floor level

During testing, the noise floor level should be measured with the sample removed, and the test fixture should be in the bypass mode. All auxiliary equipment should be turned on. Shielding effectiveness measurements may only be made to within 6 dB of the noise floor to ensure accuracy. When measurements are made outside a screen room, the tests shall be performed during times and conditions when the noise floor is at its lowest level. The noise floor level at the time of the measurement shall be recorded.

I.3.1.4 Divisions of frequency ranges and recommended sensitivity

The frequency bands selected may depend on equipment specification/ability and/or specified from predetermined requirements. Calibration of each band and bandwidth used during testing shall be verified and documented. If the measurement range is broken into several bands, then a minimum frequency overlap of 2% is recommended. A minimum number of 400 points per scan is allowed for each bandwidth only if accuracy is demonstrated and if the resolution determined is sufficient for the specified requirements. If frequency stepping is used, the minimum number of steps shall be as specified in the test method.

The sweep rate, start frequencies, and stop frequencies will be such that the equipment will be able to perform with accuracy. The resolution bandwidth should be set to the lowest possible setting, and the sweep time extended to the maximum setting for accuracy.

Using swept frequency methods is encouraged. The equipment used to perform a sweep should have tracking ability to ensure that the bandwidth and amplitude scaling is maintained and artificial attenuation is not introduced by the instrument as a result of a non-tracking bandwidth.

I.3.1.5 Attenuators, phase splitters, power splitters, and network matching pads

Attenuators that provide isolation are typically specified as having a 50 Ω impedance and a 10 dB loss. The 50 Ω input requirements should be maintained to match the 50 Ω outputs of signal generators and standard instrument that measure RF signals. 50 Ω matching pads and the 10 dB requirement should be used for non-50 Ω impedance test equipment to ensure that the voltage levels are maintained and a balanced measuring bridge is established. For other test methods and/or requirements, the input and output of the measuring bridge should match the equipment impedance to prevent overloading of the generator and provide correct signal measurements. The 10 dB requirement may be lifted and other values may be used if reasonable accuracy is maintained within the test setup.

Phase and power splitters and other specialized RF components may be required for spectrum analyzers, network analyzers, s-parameter test sets, and custom test fixtures. These devices shall meet the power and frequency requirements, and their losses shall be recorded and compensated for in the reported data.

I.3.1.6 Lead dress

In all test fixtures, input and output leads should always be separated. All cables should be doubly shielded and as short as practical. Cables used to connect to the measurement equipment should be of equal lengths. In addition, cables used in the calibration process when using attenuation pads should be of equal lengths.

I.3.1.7 Test procedure

The following test procedures should be followed: (Note: If it is found that the ambient background noise is high, then it may become necessary that testing be performed in a screen room to eliminate the influence of any outside signal anomalies.)

a) Allow at least a 15-minute warm-up of any equipment to be used in the test setup to ensure that thermal stability has been reached. Additionally, the minimum warm-up time for the entire test setup should not be less than the piece of equipment with the longest warm-up time.

b) The frequency range shall in general be broken down into different bands, as a single sweep will probably not permit sufficient resolution over the entire frequency band, and performance details such as resonances may not be detected. The actual bands may be specified or chosen on the measurement equipment such that its ability to demonstrate calibrated readings and sufficient number of points is recorded during the sweep. A minimum number of 400 points per scan is allowed if the bandwidth and accuracy are demonstrated. Frequency-stepping methods using 20 or more steps per octave may be used as an alterative method.

c) The sweep rate, start frequencies, and stop frequencies will be such that the equipment will be able to perform with accuracy and to have the dynamic range of the specification. The resolution bandwidth should be set to the lowest possible setting and the sweep time extended to the maximum setting for accuracy. Perform the sweep.

d) Prior to testing the sample under test, the loop sensors shall be verified for symmetry. Place both sensors within the center of the strip line. When both sensors are subjected to the same uniform field, the resulting transfer impedance should be ≈ 0.
The dynamic range of the test shall be determined. Place both sensors within the center of the strip line.

e) The sensor connected to the channel reading the magnetic field within the sample shall have a variable attenuator connected; 60 dB is the recommended initial setting.

f) With the amplifier and/or signal source set at minimum power, increase the power until the signal is at least 6 dB above the noise floor. This is the calibration reference for an attenuation of 60 dB.

g) Record the calibration reference for 0 dB.

h) After the desired reference level has been varied, place the sample within the strip line.

i) Perform and record the frequency sweep.

Annex J

(informative)

Electrically small enclosures in reverberation chambers

J.1 Background

This annex discusses a subject relevant to this standard and is the subject of further research in this area.

Physically small and electrically small enclosures have the potential to be measured using derivatives of the techniques described in this standard. An electrically large enclosure needs to be of sufficient volume to support a minimum of 60 modes. For a given volume, this defines a minimum measurement frequency $f_{\min}$. At frequencies less than $f_{\min}$, the techniques will not function as required. As the frequency is reduced, the multiple distinct resonant modes become apparent and the measurement of shielding becomes critically dependent on the position of the probe antenna inside the enclosure under test. Further reduction in frequency results in the enclosure under test reaching its quasi-static frequency range. For this frequency range, the largest side length dimension of a rectangular enclosure under test is less than a half wavelength. Under these circumstances, the internal field distribution of the empty enclosure under test is a combination of the evanescent (non-propagating) field distributions of the dominant mode (TE_{10}) orientated in the three orthogonal directions of the enclosure axes, the exact distribution determined by the external excitation fields. Substantial apertures or conductor penetrations into the enclosure under test will perturb this state. In the above it is assumed that the frequency remains above the minimum operating frequency of the larger outer mode stirred chamber.

Enclosures under test of a size that puts them into the quasi-static frequency range thus have a fixed internal field distribution for each of the three normal axes. Measurement of the internal field for each of these axes becomes possible. In the ideal case of a non-perturbing field probe, the measurement can be indexed to the position of the field probe measuring the normal electric field on any face of the enclosure. This is because the normal electric field distribution follows a sinusoidal spatial variation in the direction normal to that of the evanescent wave with the maximum field in the center of the face and zero at the edges where the orthogonal conducting walls force the normal electric field component to zero.

The type of sensor will also affect the measurement. In particular, if small loops are used inside the small enclosure, different results could be obtained. The choice of a monopole or loop is left to the user, because it depends on what is more similar to the final application (i.e., the victim circuit). Therefore, the presence of many final user-dependent variables makes it difficult to fix standard rules to guarantee repeatable results. Nevertheless, the use of a reverberation chamber to test small enclosures is powerful for the designer thanks to the possibility of applying a random excitation, both in polarization and incoming direction. In this way, all enclosure apertures, joints, and other defects can be excited in a quick way without changing the DUT position and orientation inside the chamber.

Finally, very small enclosures such as those mounted on printed circuit boards are likely to be deployed in situations in which they are inside a larger equipment enclosure. These very small enclosures are providing local screening for subsystems. The presence of an outer enclosure, which is not in its quasi-static frequency range enclosing a quasi-static smaller enclosure, is a similar situation to the proposed mode-stirred chamber measurement technique. Although not stirred, the outer enclosure is of undefined size and so the mode stirred measurement technique replicates the properties of a wide range of outer enclosures within a single measurement. The position of the source of the field external to the quasi-static enclosure relative to the quasi-static enclosure is important. In the scenario of the quasi-static shield providing local screening within a larger screened enclosure, the source may be within the correlation distance or frequency interval of fields within the mode-stirred measurement environment. If it is within this distance, the effect of mode stirring within the screening measurement will be reduced as will the effect of the outer enclosure on the performance of the quasi-static enclosure.

J.2 Measurement procedure

This section describes the measurement procedure that should be applied for small enclosures in reverberation chambers. Some examples of results achieved for practical enclosures are reported in this annex.

J.2.1 Distant source situation

In this case, the measurement condition simulates the presence of a disturbing source far away from the enclosure under test. The reverberation chamber is able in this case to create a superposition of infinite random plane waves resulting in a random excitation or both polarization and incoming direction. The measurement setup is the same described in 7.2.2 and 7.2.4 of this standard for multi-port approach and two-port approach, respectively.

J.2.2 Source within the correlation distance

For the case of electrically small enclosures in which the source may be within the correlation distance, it is recommended that this condition be verified by measurement of the parameter *Z* as defined in Equation (J.1). In this case, the measured *SE* will depend on the position and type of the external source as well as that of the internal sensor. These extra conditions should be included in the test report.

In the scenario of the quasi-static shield providing local screening within a larger screened enclosure, the source may be within the correlation distance or frequency interval of fields within the mode-stirred measurement environment. If it is within this distance, the effect of mode stirring within the screening measurement will be reduced as will the effect of the outer enclosure on the performance of the quasi-static enclosure. In order to evaluate this effect, a parameter *Z* has been derived as Equation (J.1):

$$Z = \frac{\left|\sum_{n=1}^{N} \left|S_n\right| \angle \theta_n\right|}{\sum_{n=1}^{N} \left|S_n\right|} \tag{J.1}$$

The coupling S_{21} between the external source to the quasi-static enclosure and the internal probe is measured during the mode-stirred measurement using a vector network analyzer. Here, S_n is the modulus of the S_{21} value measured from N_{th} stirrer position, and θ_n is the phase of S_{21} value for N_{th} stirrer position. The parameter *Z* is the ratio of the modulus of the phasor average S_{21} to the average of the moduli of S_{21} and represents the ratio of the stirred to unstirred components. It indicates the level of correlation of the coupling. A low *Z* value is consistent with classic mode stirred operation. A high value approaching unity indicates strong correlation between the coupling at all stirrer positions where the stirring is less efficient. This result has significant bearing on the proposed shielding measurement technique. It indicates that the shielding offered by the board level enclosures to nearby sources or victims will be less influenced by other factors such as the size or type of the overall equipment enclosure at lower frequencies, than will be the case at higher frequencies where the separation allows for uncorrelated coupling in the presence of such variations.

J.3 Formula to be applied

For small enclosures whose internal field is characterized by the superposition of a few modes, both power based SE and voltage based SE can be applied according to the user necessity.

J.3.1 Power based SE definition

In this case, the suggested formula is that given in 7.2.3, which uses the measured scattering param. Similar considerations hold for the mismatching correction of the inner probe. In this annex, an example of the effect produced by probe mismatching correction is reported. The way to obtain the ensemble averaged quantities (<>) are discussed in 7.2.9.

J.3.2 Voltage based SE definition

In this case, the *SE* is given in Equation (J.2) by the variation of the voltage induced on the inner sensor provided by the enclosure presence around it. (For the sensor choice and positioning, see J.4.)

$$SE = 20\log\frac{\left\langle\left|S_{31}^{ne}\right|\right\rangle}{\left\langle\left|S_{31}^{we}\right|\right\rangle} \tag{J.2}$$

where “*ne*” means “no enclosure” and “*we*” means “with enclosure.”

This definition could be very useful for the designer who wants to know how the enclosure under test reduces the voltage induced on a victim circuit. This induced voltage is responsible for circuit failure. This definition is able to highlight resonant situations in which the induced voltage could be enhanced by the enclosure resulting in a dangerous situation for the internal electronics. Unfortunately, this meaningful quantity strongly depends on the type of sensor (common mode or differential mode coupling) and on the sensor load. Loading condition is fixed by the instrument used (typically 50 Ω), but could also be varied by the user inserting impedance transformers.

J.4 Internal probe type and positioning

The choice of the enclosure internal probe, together with its positioning, is a crucial key for electrically small enclosure SE measurement.

At least three positions should be explored: mounting the probe on three main walls of the enclosure and/or orienting it along three orthogonal axes. From the designer point of view, it is suggested to mount the probe on the wall where it is expected to mount the victim circuit (e.g., printed circuits boards, sensors, critical components). In this sense, also the choice of probe type could be influenced by the final application of the equipment. For example, if the designer is concerned about a differential mode coupling, a loop could be used with a dimension similar to that of the victim circuit. This different sensor choice is of particular importance when the voltage based SE definition is applied.

Finally, when the procedure of J.3.2 is applied, the acquisition of the voltage without the enclosure requires the mounting of the probe over a reference ground plane. The side length of this reference plane should be at least $\lambda/2$ at the lowest measurement frequency.

Annex K

(informative)

Utilization of absorbing (dissipative) materials in equipment enclosures for the measurement of shielding properties

Enclosures used to house modern information technology equipment required to achieve a relatively low level of shielding. They typically have apertures for ventilation and disk insertion and their contents occupy a large fraction of the internal volume of the enclosure. The energy penetration into the enclosures and the internal field distribution is thus, in part, determined by the enclosure contents and it may be appropriate to account for the contents in the measurement of the enclosure's shielding. It is proposed that appropriate representative contents be devised for different enclosure sizes and device technologies.

Two possibilities arise:

a) Use a set of representative contents inside the enclosure-under-test during a conventional SE measurement to replicate the effects of its contents on the SE measurement.

b) Use a set of representative contents that are equipped with sensors to estimate the total energy absorbed by the contents. A new measure that relates this absorbed energy to the incident energy density could then be adopted. This technique is detailed in [B24] for frequencies up to 1 GHz and could be extended beyond that frequency.

K.1.1 Rationale and examples

The classical definition of SE relates the electric field inside an enclosure E_{int} to the field that would be present at the same point in the absence of the enclosure E_0 . It can be expressed as a ratio as Equation (K.1):

$$SE = E_0 / E_{\mathrm{int}} \tag{K.1}$$

While this definition enables the comparison of the effectiveness of various enclosures to be assessed, it does not account for the presence of contents within the enclosure, the effect those contents have on the penetration of energy into the enclosure, or the efficacy of the enclosure as a means to reduce the energy absorbed into its contents. The definition of SE is applicable for enclosures, such as screened rooms, which achieve a high level of isolation between the external environment and the internal space within the enclosure. Such enclosures have no unprotected apertures or penetrations and have been the subject of earlier versions of this standard.

Enclosures used to house modern information technology equipment are not constructed to these standards and are required to achieve a lower level of shielding. They typically have apertures for ventilation and disk insertion and their contents occupy a large fraction of the internal volume of the enclosure. The energy penetration into the enclosures and the internal field distribution is, in part, determined by the enclosure contents and it may be appropriate to account for the contents in the measurement of the enclosure's shielding.

An alternative measure that addresses these issues would have the potential to enable equipment designers to have a measure of the interference energy that will be absorbed by the contents of a given enclosure. The definition of SE given is defined for a single position of sensing antenna. At frequencies where the enclosures are resonant, the results are highly dependent on the frequency and the position of the antenna, making it difficult to compare the results from enclosures with different dimensions. This effect is addressed in the current standard using reverberation chamber techniques.

SE can also be measured for H field at low frequencies. Electromagnetic interference occurs in electronic equipment when an external electromagnetic wave impinges on the equipment and some of the energy conveyed by the wave is absorbed into the circuits of the equipment. The equipment shield is there to minimize this energy absorption. It is proposed here that an appropriate measure for the effectiveness of an enclosure could be based either on the energy absorbed by a set of representative enclosure contents when the enclosure and its contents are illuminated by an incident electromagnetic wave of defined power density or field strength, or by an internal measurement of the enclosure field in the presence of the contents.

It is possible that for some circuit types, the energy absorption is not the most appropriate measure, as for some device technologies (e.g., MOS transistors) high impulse transients can cause flashover effects and damage the circuits. However, it is likely that an enclosure containing circuits that absorb energy is less likely to resonate such that high-field strength is generated inside the enclosure. Therefore, the absorbed energy measure gives a more appropriate measure than the field based SE, which can significantly over-estimate or under-estimate the field that might be generated inside the enclosure due to an external threat.

In order to design a set of representative contents, it is necessary to observe the behavior of real contents in an enclosure. Figure K.1 shows the proposed technique. The frequency response of the enclosure with real and representative contents is compared.

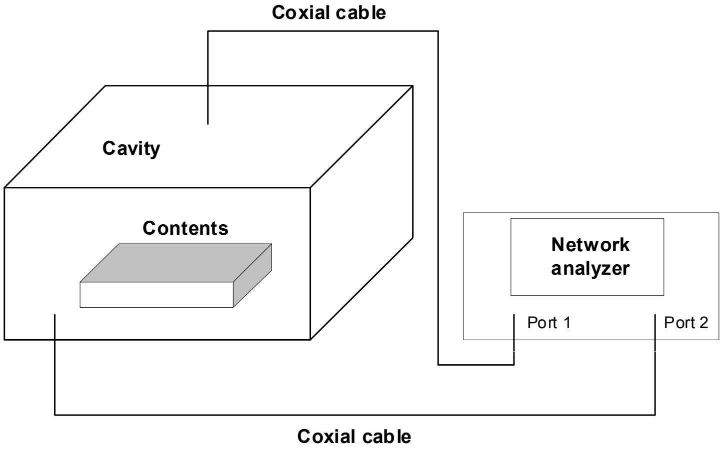

Figure K.1—Technique for observing the behavior of representative contents inside a cavity

Figure K.2 and Figure K.3 show the real contents in an enclosure and a comparison of the real contents and a set of representative contents that may be standardized. The representative contents are constructed from a sheet of carbon loaded foam set over a ground-plane. Earlier work has shown that a uniform set of contents is a good match for a complex circuit card.

Figure K.2—Photograph of real contents inside an equipment enclosure

Figure K.3—Photograph of real contents compared with representative contents

Figure K.4 shows a set of representative contents equipped with surface magnetic field probes that enable the surface current in the conducting foam to be measured. These five probe pairs enable an adequate estimate of the energy absorbed in the representative contents shown in Figure K.4.

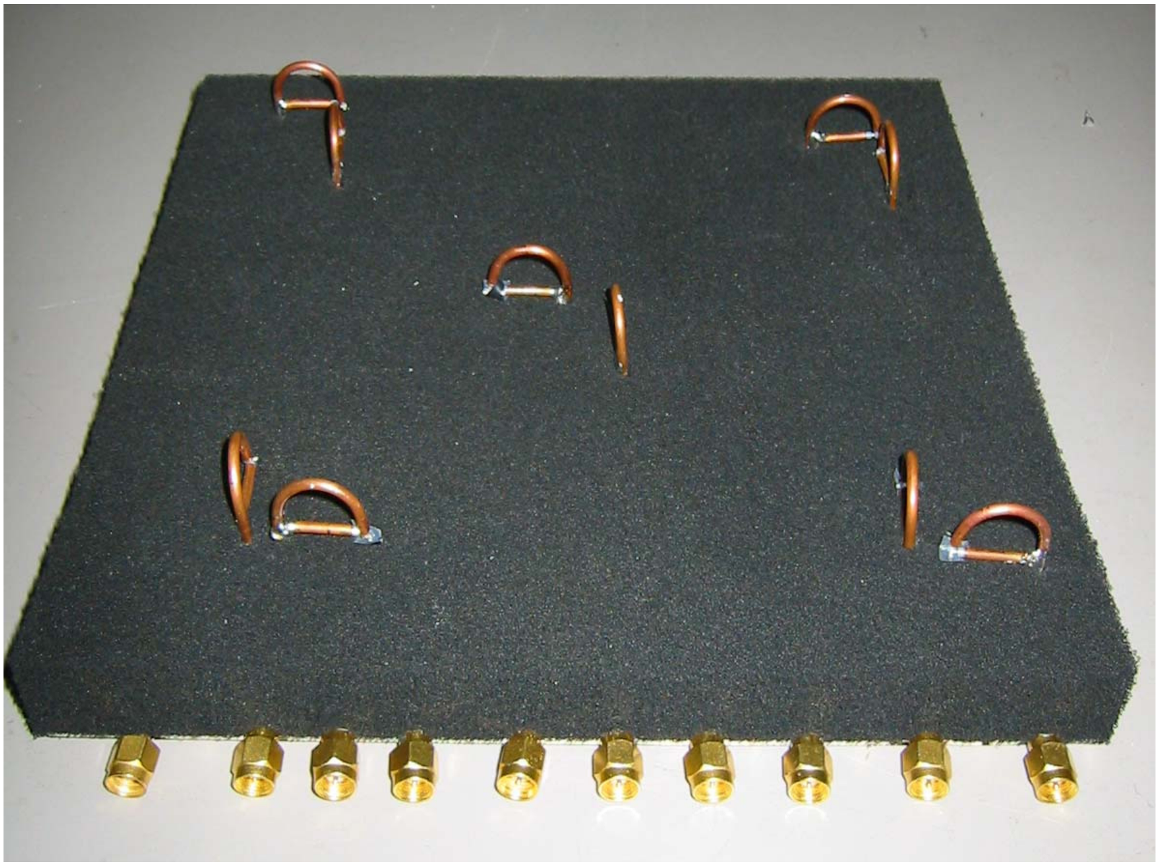

Figure K.4—Photograph of representative contents equipped with surface magnetic field probes

The plots below show the comparison between a carbon foam based set of representative contents and a typical circuit card. At higher frequencies, the mode density makes it difficult to compare the results. A technique devised by M. P. Robinson [B25] and described also in [B22] uses comparison of the width of the auto-correlation function of the frequency response between real circuit cards and sets of representative contents to overcome this problem. Figure K.5 shows an S_{21} comparison between a carbon foam based set of representative contents and a typical circuit card.

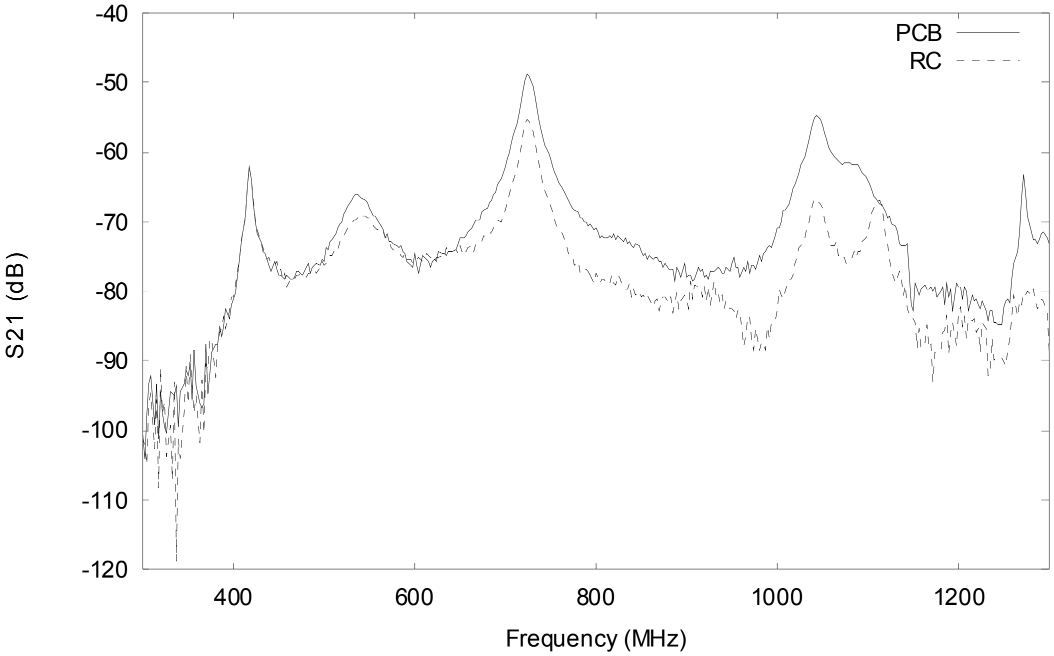

Figure K.5—S_{21} comparison between a carbon foam based set of representative contents and a typical circuit card

The three plots in Figure K.6 show the frequency response of an over-moded enclosure in the microwave frequency range. The top plot is the empty enclosure and the middle plot has a set of representative contents. The lower plot shows the autocorrelation functions of the upper plots.

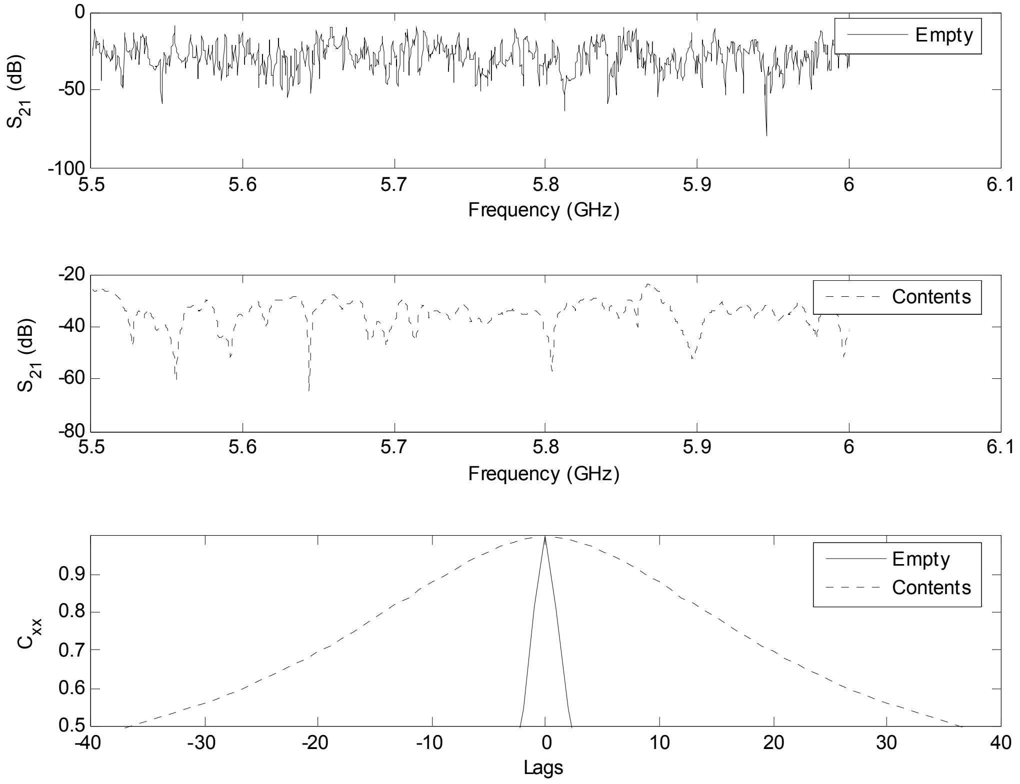

Figure K.6—S_{21} frequency response of an over-moded enclosure in the microwave frequency range

The plots shown in Figure K.7 show the maximum and minimum envelopes of the auto-correlation width for a number of different circuit cards of differing technologies. A suitable set of representative contents would have an auto-correlation width within this envelope.

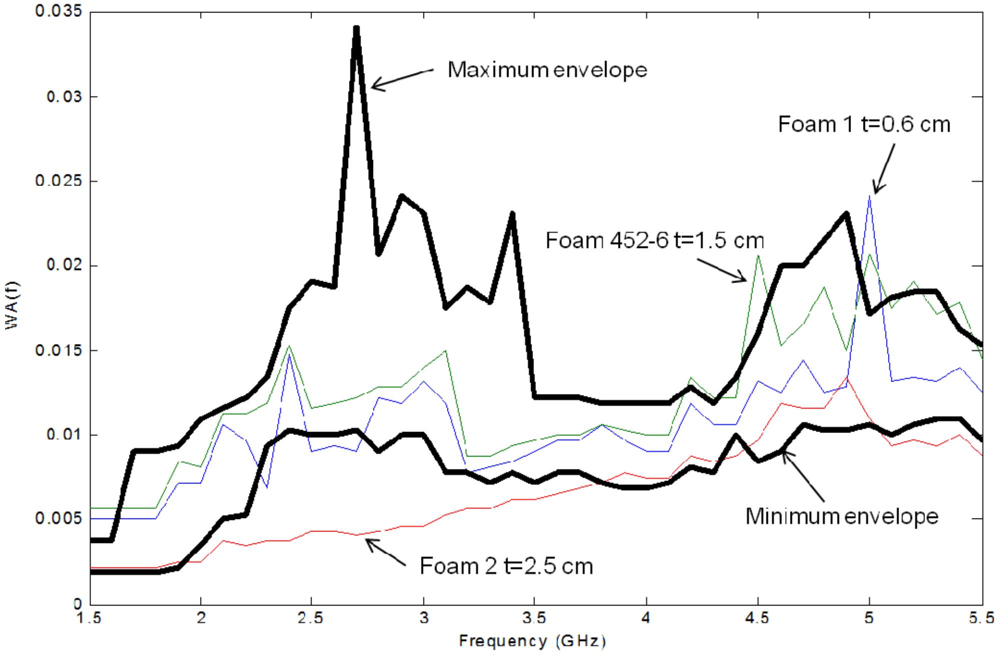

Figure K.7—Maximum and minimum envelopes of the auto-correlation width for a number of different circuit cards of differing technologies

Annex L

(informative)

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