Tadeusz W. Więckowski
Jarosław M. Janukiewicz

Wrocław University of Technology,
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
E-mail: sekretariat@ita.pwr.wroc.pl

Methods for Evaluating the Shielding Effectiveness of Textiles

Abstract
Materials with electromagnetic screening capabilities are widely used to attenuate the strength of electromagnetic fields in certain areas. Nowadays, instead of metallic shields it is more common to use various types of textile materials with the addition of special ingredients. These materials have good mechanical properties, such as being flexible and lightweight. Depending on the technology used to manufacture the different materials, we have observed the different proportions of two physical phenomena, absorption and reflection. The definition of screening effectiveness (SE) is directly related to an infinitely spread screening layer. The results of SE measurements depend on the method, frequency range, size of sample and properties of the material itself. The current state of work on standardisation and measurement methods for the SE of thin materials are also presented in this paper. The most important part of the paper is a discussion about the scope of application of the presented methods, their limitations and the possibilities for comparisons of the results.

Key words: *shielding effectiveness (SE), thin materials, electromagnetic fields, textile screening materials.*

Introduction

Shielding effectiveness is a key parameter which often determines the scope for application of a given material. Whilst we are able to determine the shielding effectiveness for metal shields just by knowing the materials' electrical and magnetic parameters, when it comes to materials containing intertwined metallic or graphite threads, plastic materials having metallised surfaces or composite materials, we are only able to determine the shielding effectiveness by actually measuring it. There are several methods available which allow the shielding effectiveness to be measured. However, for flat shielding structures, there are currently no standards defining the evaluation of small samples of only a few, several or even several tens of centimetres in size. The paper presents the authors' experiences in using shielding effectiveness measurement methods, such as modifications of the MIL-STD-285 and ASTM D4935 methods, along with the prerequisites for applying those methods. These are commonly-used methods for evaluating the shielding properties of flat materials, especially textiles.

Shielding theory

The shielding theory is based on Maxwell's equations. The currently accepted shielding theory of an infinitely spread thin surface is based on the relations originally derived by Schelkunoff [6] in 1943.

A further expansion of this theory, along with many practical implementations, can be found in the work of Shulz, Plantz & Brush [5].

Shielding is defined as the ratio of the electromagnetic field intensity measured before and after the shielding material is installed. It is assumed that the shield is an infinite plane, and that it is located between the source of electromagnetic radiation and the measuring device. The area around the source of electromagnetic radiation can be divided into three distinctive areas (Figure 1):

- the far field-area, where we observe a plane wave, and where the field's properties depend on the medium in which the wave propagates,
- the near field-area, where the field's properties depend mainly on the parameters of the source of interference and on the surrounding area,
- the transitional area at the borderline of the above two areas.

The theoretical borderline between the far field and near field is assumed to be equal to $r = \lambda/2\pi = 1$ (roughly λ/π of the wavelength - λ); in practice when we speak of the far field, the distance can be assumed as $r > 5\lambda/2\pi$.

One distinctive parameter describing the electromagnetic field is the ratio of the electrical field component E to the magnetic field component H, known as the wave impedance $Z = E/H$. For the far field, with interference propagation in an open space or air, the wave impedance is $Z = E/H = Z_0 = 377$ W. In the near field, this impedance depends on the properties of the source of the electromagnetic field, the distance of the source to the measurement point, and the propagation environment parameters. For a flat screen (see Figure 2), we can define the estimated relations (1 - 4) for the propagation environment parameters (an open space) and the screen.

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} \qquad (1)$$

$$Z = \sqrt{\frac{j\omega\mu}{\sigma}} \qquad (2)$$

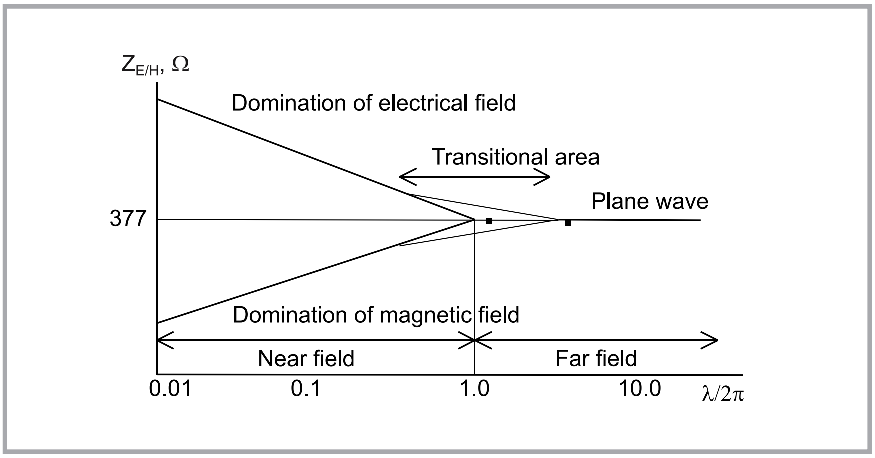

Figure 1. *Distinctive areas around a source of electromagnetic interference.*

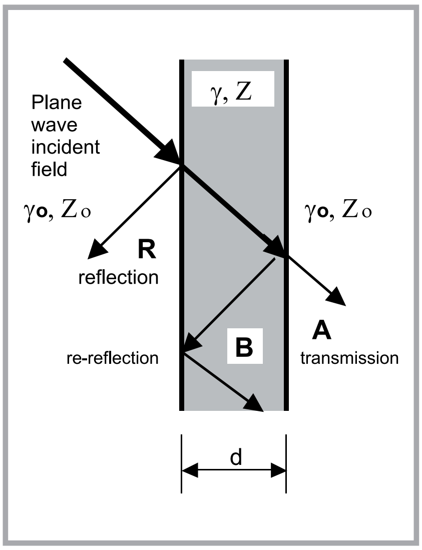

Figure 2. Shield properties affecting shielding effectiveness.

$$\gamma_0 = j\omega\sqrt{\mu_0\varepsilon_0} \tag{3}$$

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \tag{4}$$

where:
$\omega = 2\pi f$ - pulsation
ε, ε_0 - dielectric permeability
μ, μ_0 - magnetic permeability
γ, γ_0 - propagation constants
Z, Z_0 - characteristic impedance of the medium
σ - electrical conductivity
d - thickness of the shield.

The definition of shielding effectiveness is as follows:

$$\begin{aligned} SE[dB] &= 10\log(P1/P2),\\ SE[dB] &= 20\log(E1/E2),\\ SE[dB] &= 20\log(H1/H2) \end{aligned} \tag{5}$$

where the values of power P1, the electrical component E1 and the magnetic component H1 are measured without the shield, whilst the values P2, E2 and H2 are measured with the shield in place. Considering the fact that in the near field, the wave impedance linking the electrical field strength to the magnetic field strength depends on the properties of the source of the electromagnetic field, the distance to the measurement point, and the parameters of the propagation environment. Shielding effectiveness in the near field (Figure 1) will differ for the magnetic field H and the electrical field E.

Measurement methods distinguishing between far-field and near-field measurements can be found in [10] and [11].

Knowing the parameters of the shielding material, we are able to define its shielding effectiveness [5].

$$\begin{aligned} SE[dB] &= 20\log_{10}\left|e^{\gamma d}\right| + \\ &- 20\log_{10}|p| + 20\log\left|1 - qe^{-2\gamma d}\right| \\ &= A + R + B \end{aligned} \tag{6}$$

for

$$p = \frac{4\kappa}{(\kappa+1)^2}, \quad q = \frac{(\kappa-1)^2}{(\kappa+1)^2}, \quad \kappa = \frac{Z}{Z_0} \tag{7}$$

were:
A, *R,* and *B* are the components responsible for transmission, reflection, and re - reflection.

Relations (6) and (7), as well as (1-4), are used when validating the shielding effectiveness test setups. Control of the test setup consists of performing measurements using a sample with known parameters. Usually DC permeability is measured for the given sample, and on this basis, the shielding effectiveness is determined using analytical relations.

MIL-STD-285 and later standards

The MIL-STD-285 [2] method for evaluating shielding effectiveness was developed in the USA for military purposes, and was published in 1956. It is probably the most frequently referenced standard covering attenuation measurements for shielded enclosures within the frequency range of 100 kHz to 10 GHz. This standard defines the frequencies and electromagnetic field components which are subject to testing, and states the equipment required & the antenna configurations. The signal source is placed inside the tested enclosure, whilst the measurement device is located outside.

In the method often referred to as the 'modified MIL-STD-285', the material being evaluated shields an opening in a correctly shielded enclosure. Comparison measurement of the electrical field intensity *E*, magnetic field intensity *H* or power *P* with the opening open and covered with the shielding material fed into the formula (5) allow the shielding effectiveness to be determined.

The methods for measuring shielding effectiveness described in MIL-STD-285 were later replaced by those in IEEE-STD-299. This document describes methods for measuring shielding effectiveness for enclosures, although with the smallest linear dimension of such enclosure being at least 2 m. The measurement range in this method is divided into 3 sub-ranges:
- low range - from 9 kHz (50 Hz) to 20 MHz – for the magnetic component (H),
- resonant range - from 20 MHz to 300 MHz – for the electrical component (E),
- high range - from 300 MHz to 18 GHz (100 GHz) – for the plane wave power (P).

The latest revision of IEEE-STD-299-2005 does not introduce any major changes to the measurement methodology, instead adding a section dealing with measurement uncertainty.

In the future, this standard (a new revision is foreseen for 2010) is also supposed to include methods allowing for the evaluation of small enclosures and shielding materials. It should be clearly

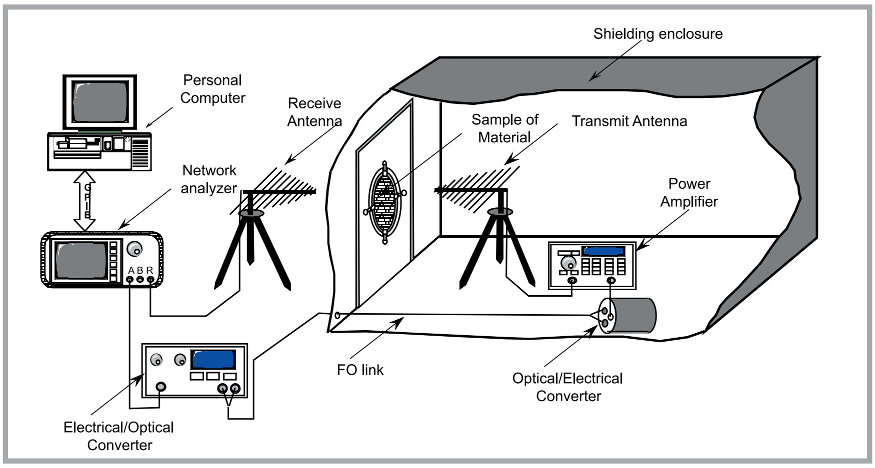

Figure 3. Adaptation of the MIL-STD-285 method at ITA PWr for attenuation measurement of thin materials.

noted that the current standard described herein only pertains to the evaluation of the shielding efficiency of large enclosures as a whole; in other words, they do not evaluate the individual properties of the shielding materials. Considering this, there are numerous adaptations of this method which have been devised to evaluate the properties of flat shielding materials.

One such test setup was implemented in 1994 at the Institute of Telecommunications and Acoustics of the Wroclaw University of Technology (ITTA PWr) [1] (Figure 3). The test area, in the shape of a 30-cm circle, was created by creating an opening in the doors of the shielded chamber. This opening was finished off with a circular collar having a stainless-steel double-spiral spring gasket, which provides excellent electrical contact with the material test samples.

An innovative solution was the use of a fibre-optic link between the external devices and the antenna inside the shielded chamber. The FO link allowed various resonance phenomena to be eliminated; these phenomena are caused by coupling between the antenna and the cable which feeds it the high frequency signal. Figure 4 presents an example of effectiveness measurement results before and after soaking the test fabric in water.

The measurement stands derived from MIL-STD-285 are usually used for 1×1m, 0.5×0.5 m square or 30-cm round test samples. There has been no major research performed to compare the different test setups, and so there is no information regarding the measurement uncertainty achieved using these setups. The current test stands are also not subject to any certification in this area. It can be expected that the test results obtained for the same material tested at different laboratories can vary, even by as much as several dB. This is because the opening in the shielded wall of the chamber also affects the measurements. This opening itself forms a type of antenna, with the parameters depending on several factors, one of which is its dimension. Taking this dimension and its effect on the shielding effectiveness measurement result into account is not easy, and there has been little research in this area.

Measuring shielding effectiveness using the above test setup is time-consuming and troublesome. It requires excellent proficiency and measurement experience from the test personnel.

ASTM D4935 method … what next?

In 1989, on the basis of a report from the NBS, the American Society for Testing and Materials (ASTM) developed and issued the D4935 [4] standard, which described a test method for measuring the electromagnetic shielding effectiveness of planar materials. The most recent revision of this document dates from 1999. In contrast to the initial version, this document specifies the scope of application for this method. ASTM regulations require technical expertise to be performed for the current standards every 5 years, in order to decide whether the standard is to remain if force or if it should be withdrawn. Document D4935-99, which is under the authority of committee ASTM D09.12, responsible for topics related to electrical parameters of insulating materials, did not receive acceptance in September 2005. The rationale given for withdrawing this standard was that the committee could not maintain a standard for which the expertise may not lie within the current committee membership. Although the document is no longer supported by the ASTM, it is still being supplied for information purposes. Also, even though this is no longer a formal standard, the method described in that document is still widely used for measuring the electromagnetic shielding effectiveness of planar materials for a plane-wave.

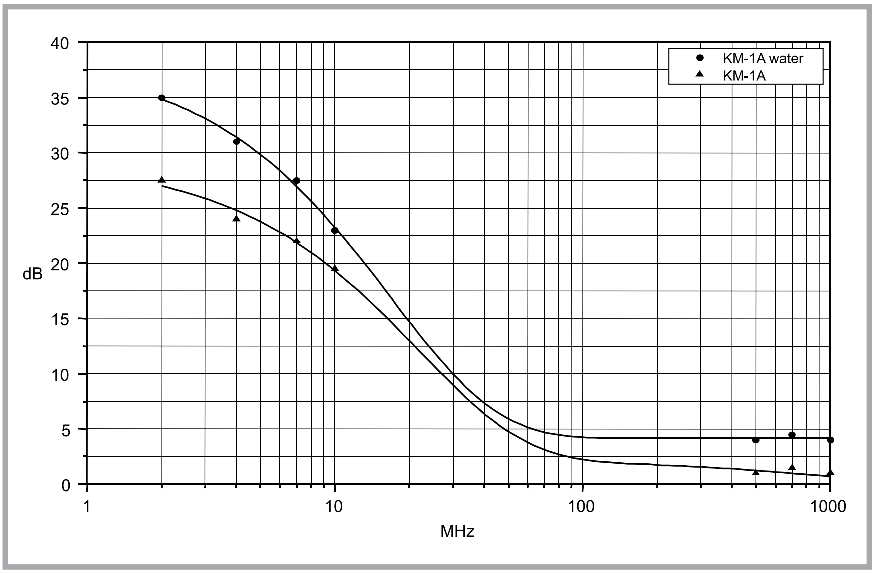

Figure 4. *Example presenting the effect of soaking the fabric on its shielding effectiveness.*

In this method, the test adapter is constructed using a section of 50 Ω coaxial aerial, having a external-to-internal diameter ratio of 76 to 33 mm (Figure 5). The shielding effectiveness measurements are carried out for frequencies ranging from 30 MHz to 1.5 GHz. In practice, measurements starting from about 1 MHz would be possible, although certain limitations arise at lower frequencies because of the capacitive coupling operation and the limited dynamic range of the measurement devices, or to be more precise, that of the network analyser used for these measurements. For frequencies above 1.5 GHz, the field inside the test adapter is no longer a TEM wave because of the induction of higher order modes. The upper frequency should not exceed the cutoff frequency for mode TE_{11}

$$f_{\max} < \frac{c}{\frac{\pi}{2}(D+d)} \qquad (8)$$

where:
c – speed of light,
D and d – diameters of the coaxial cables.

The above statement means that the upper frequency should not exceed 1.7 GHz. The test adapter is equipped with a 133-mm flange, which increases the capacitive coupling between the two halves of the measurement adapter. With a properly established test setup. the measurement uncertainty usually does not exceed ±2 dB for the above specified range of frequencies from 30 MHz to 1.5 GHz. The dynamic range provided by this test setup exceeds the method described earlier, and reaches 100 dB. The measurement device may consist of a network analyser, which is capable of measuring insertion loss and return loss. The shielding effectiveness is determined by comparing the difference in attenuation of a reference sample to the test sample, taking into account the insertion and return losses. The measurement procedure consists of two stages; in the first stage, a reference sample is placed in the test adapter to compensate for the coupling capacitance. The sample is in the form of a 33-mm circle inside a 133/76-mm ring. The second stage uses the actual test sample (Figure 5).

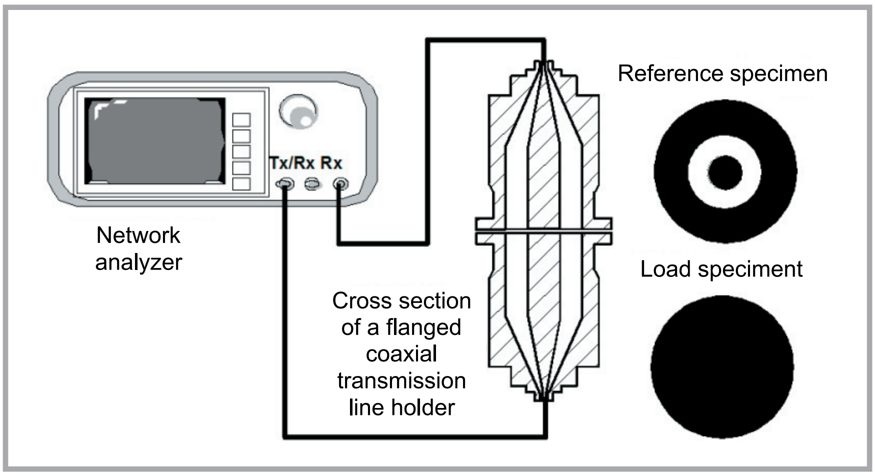

***Figure 5.** Measurement test setup for a method complying with ASTM D4935-99.*

This method can be applied assuming the following prerequisites:

- the measurements obtained pertain to the far-field (plane wave) material's parameters;
- the measurement frequency range is limited to within a range of 30 MHz to 1500 MHz;
- the thickness of the tested materials cannot exceed 1/100 of the wavelength of the EM wave in open space, i.e. the thickness of the material should not exceed 2 mm for a test frequency of 1500 MHz or 3mm for 1000 MHz;
- in the case of homogenous materials with electrical and magnetic permeabilities not related to frequency, it is sufficient to perform the measurements for just a few selected frequencies;
- for relatively thick materials and/or materials with parameters related to frequency, the measurements should be performed for the entire frequency band;
- it is necessary to ensure a fixed distance between the adapter elements (constant pressure onto the surface of the sample – identical for the test sample as for the earlier calibration sample);
- for frequencies above 200 MHz, a calibration procedure has to be performed, in order to compensate for capacitive coupling between the elements of the measuring adapter;
- the result obtained for materials with different properties depending on wave polarisation will be an average result;
- measurement uncertainty (assuming the calibration procedure has been properly performed) should fall within ± 5 dB [3], where the most important influence onto the result is caused by the 'human factor'.

The authors of this paper ran a project titled 'Development of a test methodology for small samples of planar materials and evaluation of shielding textiles and polymer-textile fabrics created during the project' at the beginning of 2005, building and commissioning a test setup allowing for planar samples to be evaluated according to ASTM D4935-99. A diagram of this test setup is shown in Figure 5.

The measurement adapter which we built (Figure 6) featured a slight improvement as compared to the original design, in order to assure better measurement repeatability. One of the changes involved removing the holding screws made of dielectric material. Here the constant pressure is achieved entirely through the large weight of the adapter. The sample is pressed down with a constant force provided by the upper half of the adapter, weighting about 7 kg. So far, several dozen samples of different shielding materials have been evaluated. The method proved effective for testing small planar samples of materials created as part of the project by the Textile Research Institute, Łódź, Poland. The major advantage of this test setup is its relatively short measurement time, which usually does not exceed 30 minutes, including all preparations for the test.

Figure 7 (page 22) presents sample measurement results obtained for the same sample measured normally (left), and with electrical insulation, by being placed inside a sheet of paper (right).

During the research project, the authors also made measurement adapters with a coaxial cable diameter ratio of diameters of 14/6 mm and flanges 44 and 33 mm (Figure 8 - page 22). The cutoff frequency for this line is 9.5 GHz. This allows the testers to extend the range of measurement frequencies further. Test measurements performed using this adapter allow us to anticipate that it will be possible to perform measurements of shielding effectiveness with frequencies ranging up to 9 GHz.

Closing remarks

Based on the deliberations and experience of the authors, it is clear that at the cur-

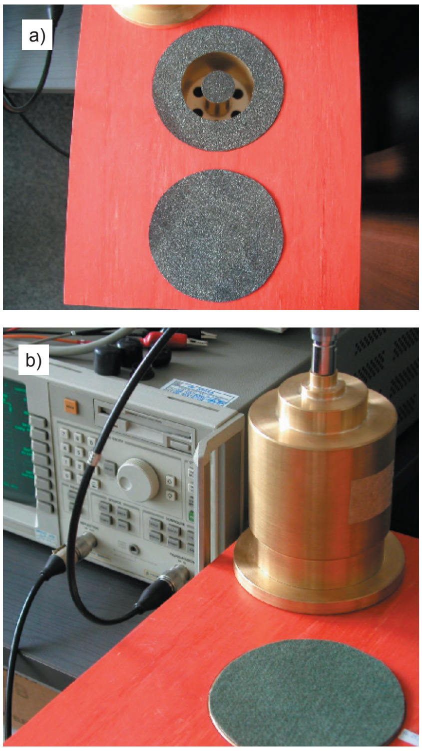

***Figure 6.** Own adaptation of the ASTM D4935-99 method at ITTA PWr: a- calibration, b-sample prepared for measurements.*

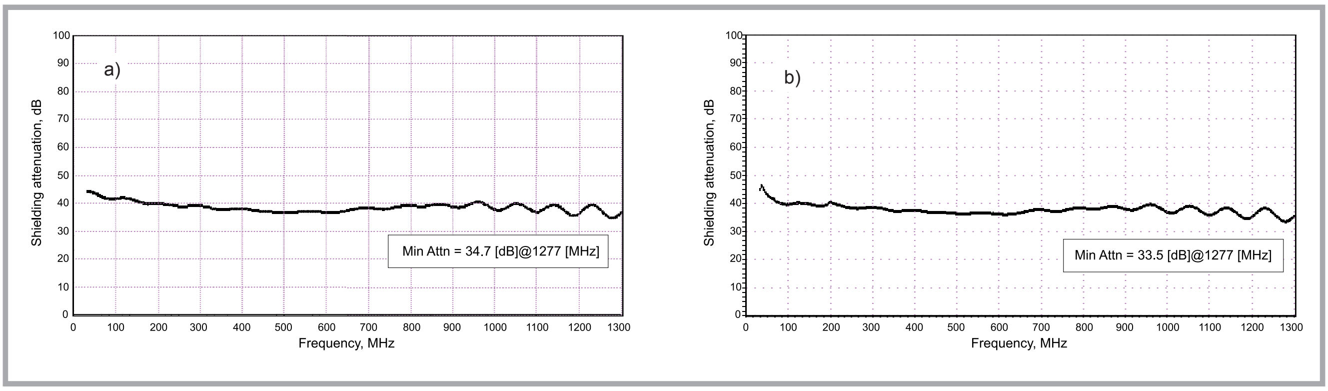

Figure 7. *Sample measurement results: a- coated fabric, b-coated fabric wrapped inside a sheet of paper.*

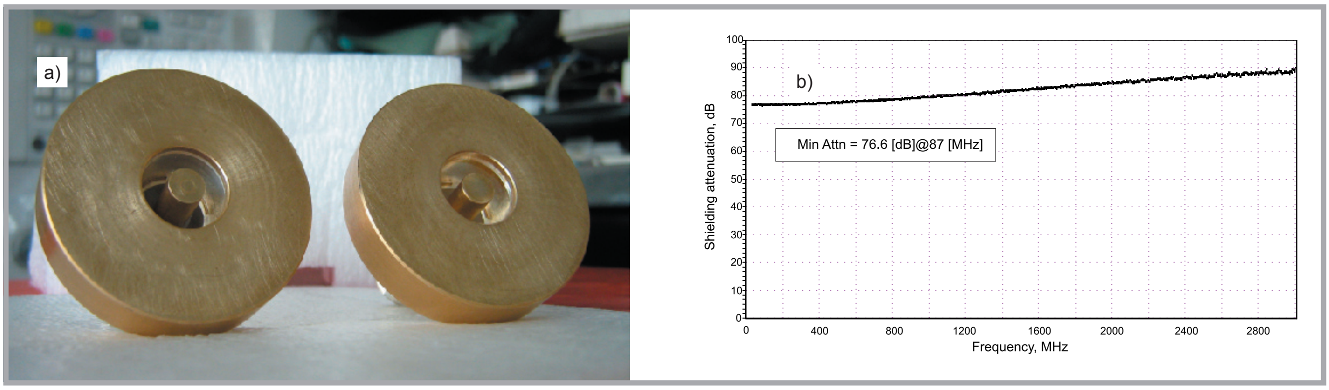

Figure 8. *Extension of frequencies foreseen by ASTM D4935: a – new measurement adapter, b – sample measurement result.*

rent state of research development there is no measurement method which would singularly define the shielding effectiveness parameters of screening fabrics/ textiles, as defined earlier in chapter 2 of this paper. The shielding effectiveness measurement results obtained using currently known methods depend not only on the properties/parameters of the shielding material, but also on the size of the test sample, the geometry of the test setup, and the parameters of the source of electromagnetic radiation. At the current state of research development, it is not always possible to take all of these additional factors into account. It should also be noted that there is currently no effective method for comparing the results of shielding effectiveness measurement obtained based on MIL-STD 285 & IEEE-STD-299 for comparison to ASTM D4935. There is also a lack of generally accepted standardised methods for measuring shielding effectiveness.

Considering this, whether developing new textile materials designed for EM shielding or modifying currently existing materials designed for that purpose, in order to check their parameters, compare them to other materials or to evaluate the effect of the implemented modifications, one should always use the same measurement method and the same test setup geometry. Also, when presenting research results, one should always specify the measurement method used along with a description of the test setup geometry. Only this approach will provide credible results for comparison (material differences, modification effects etc.).

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